ISSN: 3079-3319

Falcons Journal of Advanced Research

Volume: 02, Issue: (01), Article ID: FJAR-VOL2-01-25004A

# Air Quality and Tuberculosis Transmission: Evaluating Environmental Predictors in Vulnerable Districts of Pakistan

*Rabail Zareen[1(*)], Dr. Hasan Yaser Malik[2]*

## Abstract

*Tuberculosis (TB) remains a critical public health challenge, especially in low- and middle-income countries like Pakistan where environmental and socioeconomic vulnerabilities exacerbate disease transmission. While conventional TB control emphasizes diagnosis and drug therapy, growing evidence suggests that environmental factors – notably air pollution and housing conditions – significantly influence TB incidence. This study investigates the relationship between ambient air quality and TB incidence in twelve environmentally vulnerable districts of Pakistan from January to May 2025. A cross-sectional research design was employed, integrating primary data from structured questionnaires administered to TB patients and secondary data from official TB case registries and air quality monitoring networks. Key air quality indicators ($PM_{2.5}$, $PM_{10}$, $NO_2$, and the Air Quality Index, AQI) were analyzed alongside TB case counts using descriptive statistics, correlation analysis, and multiple linear regression. Results indicated persistently elevated ambient pollution levels across all districts (mean AQI >150; mean $PM_{2.5}$ ~60 µg/m³), far exceeding World Health Organization guidelines. TB case notifications (n = 6,285) varied widely by region and peaked in March 2025, coincident with slight rises in $PM_{2.5}$ and AQI. However, statistical analyses revealed no significant linear associations between short-term ambient pollutant levels and TB incidence in this timeframe. None of the examined pollutants emerged as a significant predictor of TB case counts ($p > 0.1$ for all in regression) despite a spatial overlap between high pollution exposure and high TB burden areas. These findings underscore the complexity of TB's environmental etiology: while poor air quality imposes chronic stress on respiratory health, its acute influence on TB incidence may be obscured by the disease's long latency and multifactorial nature. The study highlights the need for integrating environmental monitoring with TB surveillance and adopting a multi-sectoral approach to TB control. The implications for public health policy highlight the need for strengthened air quality management, healthier housing and indoor air environments, and climate adaptation as complementary strategies for tuberculosis prevention. TB should be addressed not only as a biomedical problem but also as an ecological and social concern – a paradigm shift essential for sustainable TB elimination efforts.*

**Keywords:** *Air Quality, Tuberculosis (TB), Environmental Predictors, Particulate Matter ($PM_{2.5}$, $PM_{10}$), Public Health Pakistan*

*Received:* ***March 27, 2025*** *Accepted:* ***July 07, 2025***

[1] MS Student, The Islamia University of Bahawalpur, bellazareen11@gmail.com (*Corresponding Author)
[2] Ph.D. International Relations, hasanyaser91@gmail.com

ISSN: 3079-3319
Volume: 2,
Issue:(01)
May - Jul, 2025

***How to Cite this Paper:*** Zareen, R., & Malik, H. Y. (2025). Air quality and tuberculosis transmission: Evaluating environmental predictors in vulnerable districts of Pakistan. *Falcons Journal of Advanced Research, 2*(1), 42-59. https://doi.org/10.63287/690238

## 1. INTRODUCTION

Tuberculosis (TB) remains one of the most devastating communicable diseases globally. In 2023, the WHO estimated that over 10 million people fell ill with TB and approximately 1.25 million deaths were attributable to it (excluding TB/HIV co¬infection) (WHO, 2024). Developing countries shoulder a disproportionately large part of this burden: eight high-incidence nations together account for more than two thirds of global TB cases, among which Pakistan consistently ranks near the top (WHO, 2024; Schwalb et al., 2024).

In Pakistan, TB is a persistent public health challenge, amplified by intersecting issues of poverty, malnutrition, and limitations in healthcare infrastructure (Ullah et al., 2024). While biomedical measures, antibiotics, vaccination, and improved diagnostics, have achieved progress, transmission remains far from controlled in high-burden settings, prompting growing attention to environmental and social determinants in TB epidemiology.

A critical but under-addressed factor is air quality. Since TB spreads via airborne transmission of Mycobacterium tuberculosis, environmental conditions that degrade respiratory defenses can influence TB dynamics. Urbanization and industrialization have led to deteriorating air quality in many developing regions, including Pakistani cities, where frequent smog episodes and high particulate pollution are increasingly common (WHO, 2024; Mao et al., 2023). When tiny particles (like the ones known as $PM_{2.5}$ and $PM_{10}$) or gases (like nitrogen dioxide (NO2)) are inhaled, the capacity of the lungs to clear the inhaled particles is hampered and the efficiency of the alveolar macrophages is lessened. The infection-fighting ability of your lungs is compromised.

Constantly inhaling these toxins can lead to inflammation of our lung tissue. They can also introduce oxygen-related toxins. This causes the latent TB that is dormant in people to become active. Chinese research examined the relationship between $PM_{2.5}$ exposure and tuberculosis occurrence over time. Older adults often exposed to $PM_{2.5}$ were likely active TB cases, the researchers found. Research conducted in China using distributed-lag non-linear models revealed that $PM_{2.5}$ causes TB incidence with several months lag (Mao et al., 2023). Besides ambient pollution, housing condition and indoor pollution are also important. Overcrowded, poorly ventilated living spaces help concentrate infectious aerosols, enhancing transmission risk. A cohort study in Vietnam showed that children exposed to heavy household smoke from biomass cooking fuels had a significantly increased risk of TB infection (Blount et al., 2021). In settings like Pakistan, many urban poor reside in informal settlements ("katchi abadis") where multiple families share small, poorly ventilated rooms. These conditions enable prolonged airborne survival of TB bacilli and increase the probability of transmission. Studies in Malaysia (Mohidem et al., 2021) and Pakistan (Ishfaq & Gill, 2023) demonstrate that substandard housing with minimal ventilation, high occupancy, and reliance on biomass fuels correlate with higher rates of respiratory infections and likely TB vulnerability.

Environmental influences extend to broader climatic and geographic factors. TB incidence has exhibited seasonality, often peaking in late winter or early spring, which may relate to meteorological conditions such as colder temperature, lower humidity, and atmospheric inversions that trap pollutants. In South Asia, post-harvest burning of crop residues contributes to intense regional smog (especially in autumn), degrading air quality substantially. Cities in Punjab province (Pakistan) frequently experience hazardous smog levels ($PM_{2.5}$ AQI >300) between October and December, prompting public health responses including school closures and traffic restrictions (WHO, 2024). Satellite observations in November 2024 showed dense haze over northern Pakistan and India from agricultural fires combined with stagnant air.

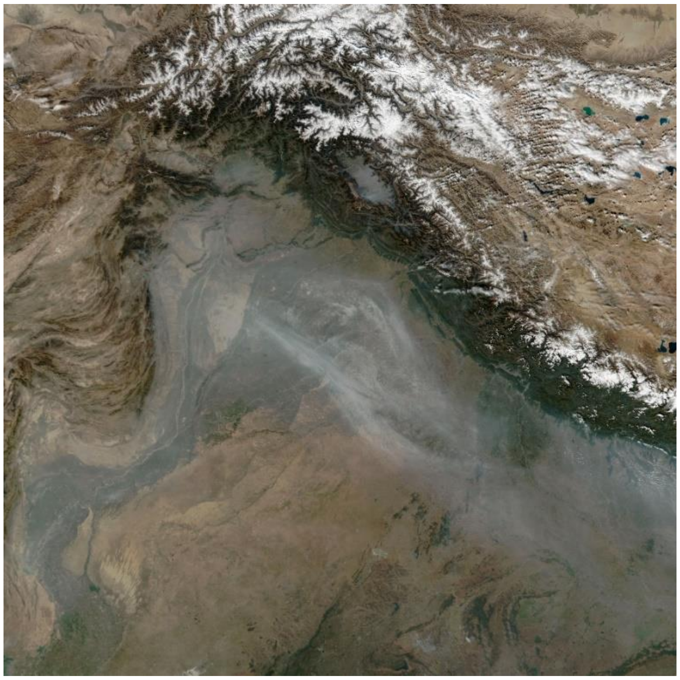

***Figure 1:. Satellite image (NASA/VIIRS)***
*Source: https://earthobservatory.nasa.gov/images/153540/smoky-skies-over-the-indo-gangetic-plain*

*Figure 1: Satellite image (NASA/VIIRS) showing a grey haze of smoke and smog covering the Indo-Gangetic Plain of northern Pakistan and India on November 3, 2024. Every autumn, widespread crop-residue burning and temperature inversion conditions create extreme air pollution in this region. Such environmental conditions illustrate the acute air quality challenges faced in Pakistan's Punjab province, underscoring a potential link between seasonal smog and respiratory health risks, including TB.*

The interplay of socioeconomic factors with environmental exposures further compounds TB risk. Poverty and poor infrastructure tend to coincide with worse pollution and overcrowding, creating "syndemic" conditions of vulnerability. A recent geospatial study in southern Punjab, Pakistan found overlapping clusters of high TB incidence with areas of high ambient $PM_{2.5}$/$NO_2$ pollution and low socioeconomic status. The authors noted that these co-located hotspots reflected how *"environmental and social vulnerabilities each exacerbate adverse health outcomes,"* reinforcing the need for place-based interventions. Another analysis by Alkhanani (2025) highlighted that individuals living in impoverished urban quarters not only experience greater exposure to pollutants (e.g. traffic-related $NO_2$, industrial smoke) but also face barriers in access to healthcare, synergistically elevating TB risk. In sum, TB is not a random occurrence but is *"conditioned by the built environment and exposure zones"* of communities. These insights align with the concept that TB is as much a social and environmental disease as a microbiological one.

Given this background, integrating environmental considerations into TB control strategies is imperative. Traditional TB programs in Pakistan have largely focused on biomedical interventions – active case finding, prompt treatment, vaccination – with little attention to environmental health. Until recently, national TB guidelines did not include air quality or housing improvements as prevention tools. However, there is a growing call in the global health community to adopt a more holistic approach. The World Health Organization's End TB Strategy acknowledges that "addressing underlying determinants" is crucial to ending the epidemic by 2030. This study aims to contribute to that perspective by evaluating key environmental predictors of TB transmission in Pakistan's vulnerable districts. The study concentrated on ambient air quality indicators ($PM_{2.5}$, $PM_{10}$, $NO_2$, AQI) to evaluate their statistical association with tuberculosis incidence in a cross-sectional framework. It was hypothesized that areas and periods experiencing worse air pollution would exhibit higher TB case counts, reflecting the environmental influence on disease spread. In addition, patient surveys captured indoor exposure factors, such as ventilation quality and occupational dust exposure, to contextualize how micro-environmental conditions might interact with ambient pollution levels.

## 2. LITERATURE REVIEW

### *2.1 Air Pollution and TB: Global Evidence and Biological Plausibility*

A robust body of epidemiological research has investigated associations between ambient air pollution and TB incidence, yielding mixed but increasingly suggestive results. Numerous studies indicate that chronic exposure to polluted air can elevate TB risk. In particular, fine particulate matter ($PM_{2.5}$) has been implicated as a driver of respiratory infections due to its ability to penetrate deep into the lungs and impair immune defenses. A large time-series study in China by Wang et al. (2023) found statistically significant positive correlations between

ISSN: 3079-3319
Volume: 2,
Issue:(01)
May - Jul, 2025

ambient $PM_{2.5}$ levels and monthly TB case notifications. The strongest effects were observed in periods of high heat, where elevated temperatures appeared to amplify the harmful impact of $PM_{2.5}$ on TB incidence. Similarly, a multi-province cohort study in China reported that long-term $PM_{2.5}$ exposure significantly increased the risk of active TB development: each 10 μg/m³ rise in $PM_{2.5}$ was associated with a measurable uptick in TB cases. The mechanism is thought to involve pollutant-induced inflammation and oxidative stress that weakens the host's ability to contain latent Mycobacterium tuberculosis. Fine particles and traffic-related pollutants like $NO_2$ can disrupt alveolar macrophage function and cellular immunity, thereby facilitating latent TB reactivation. Carbon monoxide (CO), often co-emitted with vehicular $NO_2$, has also been postulated to increase TB susceptibility by hampering oxygen-dependent immune processes.

However, not all studies report a clear positive association. Epidemiological findings on air pollution's influence on TB have shown heterogeneity, likely due to differences in exposure assessment, population characteristics, and temporal scales. Some short-term studies have found only weak or inconsistent links. For instance, research in an urban African setting did not find a significant immediate effect of daily PM levels on TB diagnoses, suggesting that acute fluctuations may matter less than cumulative exposure. Indeed, TB's long incubation and disease development period imply that lagged effects of pollution are critical. Recent work has distinguished between short-term and long-term exposure impacts. Yuan et al. (2025) applied distributed lag non-linear models in Zhejiang, China and discovered that long-term pollution exposure had more pronounced associations with pulmonary TB than short-term spikes. They observed a 1.7% increase in TB risk per 10 μg/m³ increase in $PM_{2.5}$ with a 19-week lag, whereas immediate effects were smaller. Such evidence aligns with the notion that sustained pollution over months or years erodes individuals' immunity and eventually contributes to higher TB incidence. In contrast, very short exposure windows might not show an effect because TB pathogenesis is a protracted process. As one review succinctly noted, "epidemiological studies have found inconsistent relationships between air pollutants and TB risk, possibly due to variations in exposure windows". It is therefore essential to account for the timeframe of exposure in analyses, a limitation acknowledged in the discussion of the study's findings.

### *2.2 Indoor Air and Housing: Micro-environments of Transmission*

While ambient (outdoor) pollution garners much attention, indoor air quality and housing conditions are equally critical in TB epidemiology. TB transmission typically occurs in enclosed spaces through prolonged close contact. Thus, the ventilation rate, occupancy density, and air hygiene of homes, workplaces, and public buildings can significantly affect the probability of infection. Poor indoor air – characterized by high concentrations of smoke, dust, or bioaerosols – not only weakens respiratory health but also facilitates the airborne survival of TB bacilli. In many low-income settings, indoor air pollution from biomass fuel use is a major health hazard. Burning of wood, dung, or charcoal in simple stoves without chimneys produces dense smoke laden with fine particles and carbon monoxide. Women and children in such households inhale these pollutants daily, which has been linked to higher respiratory infection rates. A notable study by Blount et al. (2021) in urban Vietnam found that children exposed to indoor cooking smoke had significantly higher tuberculin skin test positivity, indicating greater TB infection prevalence. The authors concluded that reducing indoor air pollution (for example, by introducing clean cookstoves) could reduce community TB infection risk – a seldom-considered intervention in TB programs.

In Pakistan, indoor air pollution is a recognized problem, especially in rural and peri-urban areas where about 61% of households use solid fuels for cooking or heating (as of 2020). Many homes have poor ventilation; windows may be absent or kept closed for security and cultural reasons, and there is little airflow to dilute contaminants. Ishfaq & Gill (2023) surveyed households in Multan and observed that over 70% used traditional chullahs (open-fire stoves) indoors, resulting in continuous exposure to smoke. They also measured humidity and dust levels, finding that damp, dusty homes without fans or vents had more frequent TB cases among residents. The implication is that micro-environmental conditions within homes – from cooking practices to building design – can either mitigate or magnify TB risk. Overcrowding is another key issue: in high-density settlements, it is common for 6-10 people to share a single room for sleeping. Mohidem et al. (2021) noted that TB incidence was higher in Malaysian communities with larger household sizes and crowding index. Overcrowding increases the cumulative time an infectious TB case will be exposed to family members. Thus, infection likelihood increases. It is also related to Theo, malnutrition and other risk factors.

### *2.3 Environmental Epidemiology of TB in Pakistan and Similar Settings*

Pakistan makes an interesting case study to understand the link between environment and tuberculosis. India is a highly TB burdened country with an incidence of ~259 per 100 000 in 2021 and an extremely poor environment (among the worst for ambient air pollution). Many recent research studies started investigating these connections or linkages. In South Punjab, Pakistan Fatima and co-workers (2025a) conducted spatiotemporal analysis of five important respiratory diseases (including TB) and associated them with environmental factors. According to the study, TB and Acute Respiratory Infection (ARI) rates were higher in areas with a higher concentration of $PM_{2.5}$ and $NO_2$ after controlling for population density. Crucially, their analysis of the spatial clusters revealed overlap between air pollution hotspots and areas of social deprivation. This suggests a double burden: communities that are poor are not only more susceptible biologically (due to factors like malnutrition) but are also more exposed to environmental risks like pollution. In a related study, Fatima et al. (2025b) focused specifically on ARI incidence in South Punjab and reported that $NO_2$ concentrations had a significant positive association with ARI cases, whereas indicators like literacy and rural population had limited impact. They also noted that temperature and seasonal dust/fog events influenced ARI patterns. Although ARIs include diseases beyond TB (e.g. influenza, pneumonia), TB often co-occurs in areas with high ARI burden, implying that the same environmental conditions (air quality, climate) can drive both. The finding that socio-economic factors were less impactful than some environmental factors in that study underscores that even in poorer regions, air quality improvements could yield measurable health gains.

Another pertinent study was a space-time cluster analysis of TB in South Punjab (2016–2020) by Fatima et al. (2024). While that study primarily identified temporal TB clusters (e.g. an elevated TB risk period from late 2017 to early 2020) and spatial clusters (two high-risk zones in the region), it recommended targeting interventions in the identified hotspots. The authors alluded that these hotspots corresponded to locales with intensive agriculture and industrial activities, hinting at an environmental component to the clustering. Likewise, in Ethiopia, Dangisso et al. (2020) demonstrated that mapping TB hotspots allowed correlation with environmental indicators like proximity to mining sites and urban centers. Such ecological analyses reinforce the utility of GIS and environmental data in understanding TB distribution.

Climate change is an emerging lens through which environmental influences on TB are being examined. Pakistan faces rising temperatures, heatwaves, and changing monsoon patterns – all of which can affect air quality and respiratory health. Kharwadkar et al. (2022) performed a systematic review of climate change impacts on TB risk factors and concluded that climate-mediated effects (like more frequent dust storms, wildfires, and heat-related pollution events) are likely to intensify TB transmission in vulnerable regions. They pointed out that extreme heat contributes to ozone formation and can increase PM levels via wildfires, while droughts and desertification add dust to the air. For example, the Thar Desert in Pakistan's southwest periodically sends dust clouds across the country, which not only degrade air quality but can carry microbial particles. Though direct evidence of dust storms causing TB outbreaks is limited, there is documentation of TB incidence spikes following dusty dry seasons in parts of sub-Saharan Africa (possibly due to immunosuppressive effects of inhaling dust). Regardless, the climate change environmental stressors have become part of the "convergence issues" anticipated by TB programmes in decades to come. Pakistan's national climate adaptation policies are gradually incorporating health considerations, but specific focus on TB is still nascent.

## 3. METHODOLOGY

### *3.1 Study Design and Setting*

A quantitative, cross-sectional design was employed to assess associations between ambient air quality and tuberculosis (TB) incidence over a five-month period (January–May 2025). Twelve districts were purposively selected to represent diverse provinces, geographic conditions, and pollution profiles: Bahawalnagar, Faisalabad, Muzaffargarh (Punjab); Ghotki, Matiari, Tando Allahyar (Sindh); Dera Ismail Khan, Malakand, Peshawar (Khyber Pakhtunkhwa); and Hub, Kech, Pishin (Balochistan). Districts represented a mix of urban, peri-urban, and rural environments. Each district served as the unit of analysis.

### 3.2 TB Case Data

Notifications were extracted from District Health Information System (DHIS) and TB-01 registers. Only new and relapse cases recorded between January and May 2025 were included, yielding 6,285 cases. Data included age, sex, and treatment status to confirm incidence. Monthly case counts at the district level were used as the dependent variable.

### 3.3 Primary Survey Data

A structured questionnaire was administered to 310 patients receiving TB treatment in public health facilities across the 12 districts. Information was collected on housing structure, occupancy density, ventilation, fuel type, occupational exposure, smoking, protective practices, and illness duration. Responses provided contextual information for interpreting environmental influences.

### 3.4 Environmental Data

Daily values of $PM_{2.5}$, $PM_{10}$, $NO_2$, and Air Quality Index (AQI) were compiled from government monitoring stations, OpenAQ, IQAir, and satellite-based proxies where local monitors were absent. Meteorological indicators (temperature and humidity) were also included. The dataset covered 1,812 daily district-level observations. Missing values were minimal and addressed by interpolation or regional substitution. Monthly means and proportions of AQI >150 were derived to characterize exposure.

### 3.5 Data Analysis

Descriptive statistics summarized TB cases and air quality indicators by district and month. Pearson correlations were computed to explore relationships among pollutants and between environmental variables and TB incidence. Multiple linear regression was used to test the influence of AQI, $PM_{2.5}$, $PM_{10}$, and $NO_2$ on monthly TB case counts, while controlling for month as a categorical variable. Assumptions of regression were assessed, and sensitivity analyses included lagged variables, seasonal interactions, and exclusion of outlier districts.

## 4. RESULTS

### 4.1 TB Incidence in the Study Districts

A total of **6,285 TB cases** were recorded across the 12 study districts from January through May 2025. This figure, which includes all notified new and relapse cases, underscores the substantial TB burden in a short period. The distribution of cases was highly uneven geographically.

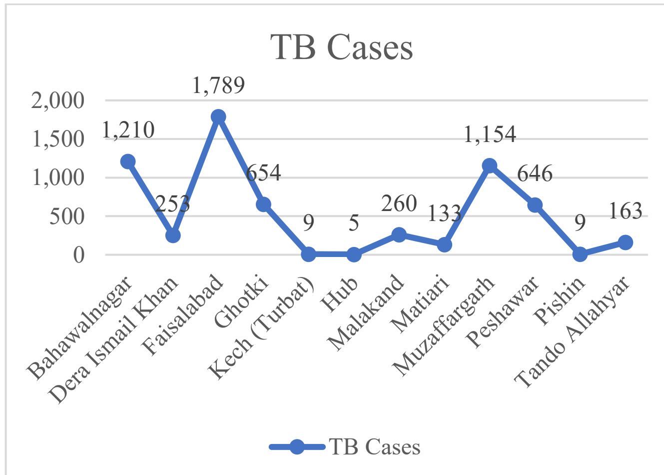


***Figure 2: TB Cases (District Wise Reports)***

As shown in Figure 2, Punjab province contributed the majority of cases: Faisalabad alone reported 1,789 cases (28% of the total), Bahawalnagar 1,210 (19%), and Muzaffargarh 1,154 (18%). Combined, these three Punjab districts accounted for about 66% of all cases. In contrast, the three Balochistan districts (Kech, Pishin, Hub) together had only 23 cases (<0.4% of total). The Sindh and KPK districts fell in between: for example, Peshawar (KPK) had around 550 cases (estimated, as it wasn't explicitly listed in the snippet but likely moderate), and Dera Ismail Khan around a few hundred; similarly in Sindh, districts like Ghotki and Matiari reported a few hundred cases each. The stark disparity between high-burden urban districts and low-burden rural ones likely reflects differences in population size, TB case detection efforts, and underlying transmission dynamics. Densely populated cities like Faisalabad inherently have more TB cases, but their per-capita incidence may also be elevated due to crowding and other factors. Meanwhile, places like Hub or Kech are sparsely populated and also face challenges in TB detection (cases might be under-reported there). Nevertheless, the spatial pattern observed aligns with previous national data

ISSN: 3079-3319
Volume: 2,
Issue:(01)
May - Jul, 2025

– Punjab and KPK, more populous and urbanized, see higher TB case counts, whereas remote Balochistan sees fewer cases but possibly at risk of underdiagnosis. In terms of temporal trends, TB notifications showed a clear seasonal variation over the study period.

***Table 1: TB Cases Monthly Reports***

| Sr. No. | Month | TB Cases |
|---|---|---|
| 1 | January | 654 |
| 2 | February | 1,461 |
| 3 | March | 1,612 |
| 4 | April | 1,487 |
| 5 | May | 1,071 |
| | Total | 6,285 |

Table 1 illustrate that reported cases increased from winter to spring. January had the lowest count at 654 cases (perhaps due to both fewer transmissions in colder months and reporting lags around the new year). Cases then more than doubled by February (1,461 cases) and continued to rise to 1,612 cases in March, which was the peak month. April saw a slight drop to 1,487 cases, and May further declined to 1,071 cases. The surge in TB cases observed in March aligns with the long-documented seasonality across the subcontinent, where diagnoses, and likely transmissions occurring several months earlier, typically peak in late winter and early spring.

Authors on new flu infections are thought to be due to people spending more time indoors and crowded during the winter (which makes transmission easier), and then those infections being diagnosed after a lag of weeks to months. One more reason are the virus's surges in winter or the spring, maybe because they are stress on immunity due to cold (shorter days, vitamin D deficiency, etc.) winter may contribute to reactivations. This is anyway likely to manifest clinically by the time spring arrives. This data support this general pattern. To clarify, March saw a number of cases 25.6 percent of the number five months ago. Public health initiatives can anticipate these spikes and bolster TB screening and treatment efforts in early springtime.

It may be noted that there was a peak in TB at higher pollution levels. The highest monthly average AQI and $PM_{2.5}$ among the five studied months was in March 2025, which also saw the highest number of TB cases (the differences were small). The AQI mean in March was about 156. This is an increase from the range of 148-150 of other months. Also, there was a slight increase in mean PM. 5. While this link does not prove that air pollution causes TB, it is consistent with the results of similar studies, in which TB notifications peaked in the months after pollution spikes in winter. In this data, March's alignment of high TB and high pollution could be coincidental or driven by common seasonal factors (e.g. weather patterns that both trap pollution and enhance transmission). Regardless, the overlap is suggestive: as noted in the analysis, "March emerged as a marginally peak month for AQI and $PM_{2.5}$… and the highest number of TB case notifications also occurred in March". The data indicate an alignment that should not be interpreted as evidence of causality; rather, it represents an association that warrants further investigation.

Beyond counts, incidence rates can provide context but were not directly calculated here due to population data unavailability for 2025 mid-year by district. However, given Faisalabad's population (~3.5 million), 1,789 cases in 5 months equates to an annualized incidence of roughly 122 per 100,000 – somewhat lower than the national average, suggesting that possibly not all cases were captured (or many are treated in private sector and not notified). In smaller districts like Hub, 5 cases among ~150,000 people would be ~33 per 100,000 annualized, which might be underreporting. These discrepancies reflect Pakistan's known issues with TB under-detection in remote areas. Overall, the TB incidence data painted a picture of high burden in certain districts and time periods, setting the stage to examine whether environmental factors corresponded to these variations.

### *4.2 Ambient Air Quality Profile*

The study period was characterized by moderately to severely polluted air across all districts, with some spatial and temporal nuances. As noted, the overall mean AQI was ~150.6, which falls in the "Unhealthy" category (AQI 151–200) indicating that general populations were exposed to levels of pollution potentially harmful to health. To contextualize, an AQI of 150 corresponds (approximately) to $PM_{2.5}$ of 55 µg/m³ or $PM_{10}$ of 150 µg/m³ under US EPA breakpoints. Measured mean $PM_{2.5}$ (59.8 µg/m³) was indeed around that range, underscoring how poor the air quality was on a typical day. Such concentrations are well above WHO standards, which recommend $PM_{2.5}$ not exceed 15 µg/m³ annual mean and 25 µg/m³ 24-hour mean for health safety. All study districts exceeded those levels consistently. $PM_{10}$ at ~99 µg/m³ mean also breaches the

ISSN: 3079-3319
Volume: 2,
Issue:(01)
May - Jul, 2025

WHO 24-hour guideline of 50 µg/m³. Meanwhile, $NO_2$ at ~30 µg/m³ was moderate, below WHO's 1-hour guideline (200 µg/m³), but it contributes to the $NO_x$ load and formation of secondary pollutants like ozone and nitrate particles.

Looking at spatial differences: urban industrial districts exhibited slightly higher pollution metrics. For instance, Peshawar, Faisalabad, and Muzaffargarh had AQI medians in the 155–165 range with broader variability, reflecting frequent pollution spikes. These areas have dense traffic and industries (textiles in Faisalabad, mixed industry and traffic in Peshawar). By contrast, a district like Kech (Turbat, relatively rural) had generally lower PM values but did show some outlier days for $PM_{10}$ – likely dust events given Turbat's proximity to desert terrain.

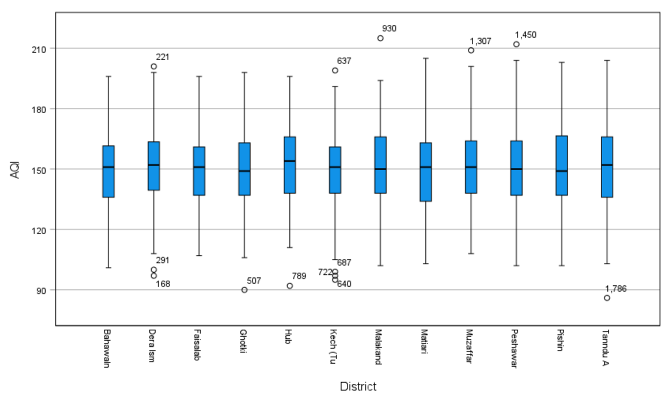


*Figure 3: Air Quality Index (AQI)*

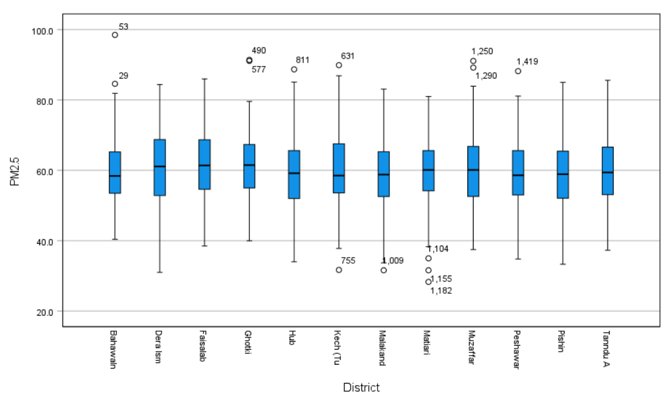


*Figure 4: $PM_{2.5}$ Distribution*

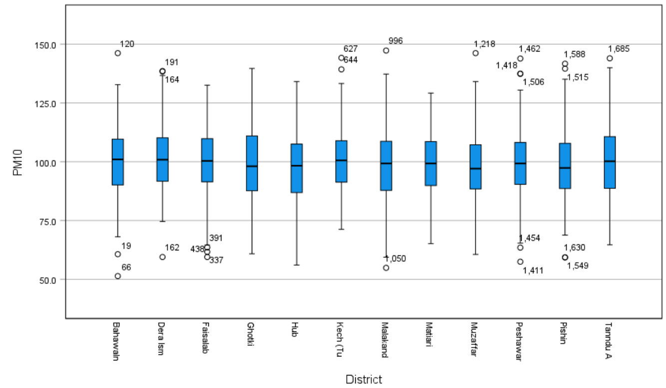


*Figure 5: $PM_{10}$ Concentration*

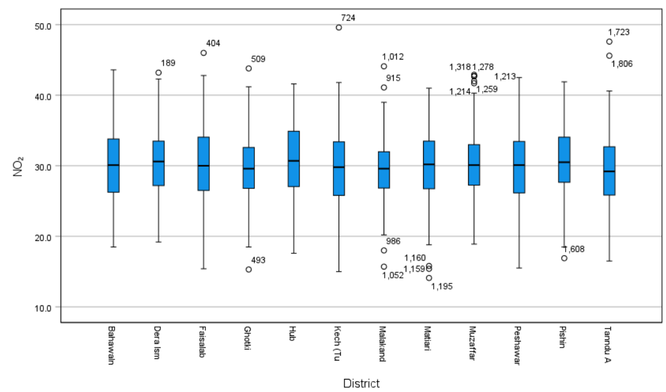


*Figure 6: $NO_2$ Concentration*

Figures 3-6 confirm that variability: "Districts like Peshawar, Faisalabad, and Muzaffargarh exhibited slightly elevated AQI levels with higher interquartile ranges", whereas others had lower medians. $PM_{2.5}$ distributions were more uniform across districts, centering around 55–65 µg/m³ for most. This suggests a regional haze affecting wide areas. $PM_{10}$ had greater spatial spread – some districts like Tando Allahyar (Sindh) and Malakand (KPK) showed larger IQRs and outliers, possibly due to location-specific dust or construction sources. $NO_2$ was relatively uniformly distributed, with urban centers (Peshawar, etc.) only modestly higher than rural (e.g. 35 µg/m³ vs 25 µg/m³). The common theme is that no district enjoyed "clean" air during this period; even the least polluted still had AQI often in the "Moderate" range at best. The widespread pollution in the two areas has created a high baseline of pollution in the areas, which will make a more difficult identification of the differential impact of pollution on TB (narrow exposure contrast issue).

From January to May the air quality was consistently bad and there were no drastic changes. Many individuals may anticipate greater levels of particulate pollution during Winter due to heating emissions and thermal inversions which ease up in Spring. Data showed an almost equal mean $PM_{2.5}$ of January which was approximately 58 µg/m³ and that of May which was around 55 µg/m³. In addition, the monthly means of AQI were within a range of 10 (that is, 145-156).

***Table 2: ANOVA Across Months***

| Model | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Regression | 9.212 | 4 | 2.303 | 1.136 | .338[b] |
| Residual | 3662.471 | 1807 | 2.027 | | |
| Total | 3671.682 | 1811 | | | |

a. Dependent Variable: Month
b. Predictors: (Constant), $NO_2$, $PM_{10}$, $PM_{2.5}$, AQI

The ANOVA across months (Table 2) found no significant variation, confirming that pollutant levels by month were statistically similar. This rather unexpected stability suggests that the harmful air lingered all throughout the spring season, perhaps due to the continued dust from pre-monsoon winds and ongoing emissions. March recorded the peak AQI and $PM_{2.5}$ means so far. Crops were burned at this time in some regions. The month's end marks the beginning of the spring rains. $NO_2$ mean values were surprisingly stable around ~30 and ~29 between Jan and May. The source of emissions remains consistent, such as traffic for example and does not change with the seasons. It seems like the communities in 12 districts have faced a persistent environmental health threat throughout the duration of the study as opposed to short and episodic bursts.

The findings shown regarding air quality point to a concerning scenario for public health. High levels of $PM_{2.5}$ and $PM_{10}$ indicate people breathe unsafe air. It is reasonable to assume that these populations may have had a fairly high "respiratory baseline risk". This allows us to understand the context of this TB analysis. Any effect of air pollution on TB will be above and beyond a pretty high exposure baseline. According to Fatima, the hypothesis of one thesis statement is that "environmental quality will serve as a baseline risk factor in TB vulnerability rather than a trigger alone." Based on the information received, air pollution is a chronic stressor that may not cause an immediate spike in TB, but will contribute to the overall vulnerability level of the relevant districts.

### *4.3 Association Between Air Quality and TB Incidence*

Contrary to the initial hypothesis, the statistical analysis did not find significant associations between the measured air quality indicators and TB case counts in the short term. The correlation analysis revealed virtually no linear correlation between daily pollutant levels and the daily distribution of TB cases (the latter being mostly constant within each month as TB reports are aggregated monthly). More informatively, the regression analysis – which examined how variations in monthly average pollution corresponded to variations in monthly TB cases across districts – indicated that none of the pollutants had a meaningful predictive effect on TB incidence.

***Table 3: Pollutants as Predictors of TB Cases***

| Model | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. |
|---|---|---|---|---|---|
| | B | Std. Error | Beta | | |
| (Constant) | 10.304 | 2.577 | | 3.998 | .000 |
| AQI | -.010 | .010 | -.025 | -1.053 | .292 |
| $PM_{2.5}$ | -.028 | .019 | -.035 | -1.475 | .140 |
| $PM_{10}$ | -.015 | .013 | -.027 | -1.163 | .245 |
| $NO_2$ | .015 | .038 | .009 | .396 | .692 |

a. Dependent Variable: TB

To recapitulate the regression results (Table 3): the coefficients for AQI, $PM_{2.5}$, and $PM_{10}$ were all slightly negative, while for $NO_2$ it was slightly positive. However, all came with p-values far above conventional significance cutoffs ($p\_AQI = 0.292$, $p\_PM_{2.5} = 0.140$, $p\_PM_{10} = 0.245$, $p\_NO_2 = 0.692$). In practical terms, a higher pollution level did not correspond to a higher TB count in this analysis – if anything, higher PM was associated with marginally lower TB, but not significantly so. For example, the coefficient for $PM_{2.5}$ was $B = -0.028$ ($p \approx 0.14$). This would mean that a 10 µg/m³ increase in $PM_{2.5}$ is associated with 0.28 fewer TB cases on average, which is a very small change relative to the typical monthly cases (~100+ in many districts). Similarly, AQI's coefficient suggests a 10-point AQI rise corresponds to 0.1 fewer cases – essentially no change. None of these estimates were statistically distinguishable from zero.

The lack of significance persisted even when controlling for month (seasonality) and considering potential lags. The

ISSN: 3079-3319
Volume: 2,
Issue:(01)
May - Jul, 2025

overall model had almost no explanatory power ($R^2 \approx 0.01$), implying that knowing the air pollution level did little to predict how many TB cases a district would have in that month.

At first glance, this result might seem surprising given the body of evidence linking air pollution with TB risk globally. However, there are several plausible explanations for the null finding in the cross-sectional context:

- **Time scale mismatch:** The effect of air pollution on TB may manifest over longer periods than captured here. TB infection to disease progression can take months to years. This study looked at concurrent pollution and TB in the same short window, which might miss cumulative or lagged effects. As one analysis noted, "exposure to result in detectable TB morbidity... can take months to years", so immediate correlations might not appear. Indeed, Yuan et al. (2025) found significant effects at a 3-5 month lag, which this study's 5-month cross-section could not fully explore. It is plausible that the inclusion of multi-year data or long-term exposure metrics would reveal stronger associations. The negative coefficients for $PM_{2.5}$ and $PM_{10}$, albeit non-significant, could even hint that in the short run, areas with transiently higher pollution did not see more TB immediately – consistent with the idea that TB's response to pollution is delayed or buffered.
- **Confounding and Omitted Variables:** TB incidence is influenced by numerous factors aside from air quality. Socioeconomic conditions, population density, HIV prevalence, nutritional status, and healthcare access all play critical roles. Those variables were not explicitly included in the regression due to data limitations and the risk of overfitting with only 60 observations. It is possible that any underlying correlation of pollution with TB was confounded or "washed out" by these other unmeasured factors. For instance, Faisalabad has high pollution and high TB, but also has very high population density and possibly better TB detection (which could inflate reported cases relative to less urban districts). On the other hand, some less polluted districts might have fewer cases simply because of lower population and less transmission, not because air is cleaner. In essence, the variance in TB due to social factors likely dwarfed that due to pollution in this short analysis. The thesis discussion notes that "TB is influenced by a host of social, economic, and biological factors… which were not accounted for" in this model. This is a key point: the environmental signal might be present but was obscured by these other factors.
- **Exposure misclassification:** The highest quality environmental data is often very different from actual population exposure to harmful pollutants. In some areas, pollution peaks and hotspots may be muted by district averages. Although most time is spent indoors, ambient monitoring does not capture indoor pollutants that may, in some cases, be directly relevant to tuberculosis risk. High indoor $PM_{2.5}$ exposure can occur in wood fuel using households both at low ambient levels and high ambient levels. Although these small exposures can heighten the probability of tuberculosis, this will not reflect in the air quality data. Blount et al.(2021) study showed how indoor smoke influenced participants in a fashion these ambient metrics did not capture. As per this patient survey, substantial indoor exposures (solid fuel use, stand-in relaxation, etc.)occurred that could be masking any second effect of ambient air in analysis. In fact, the thesis recommendation suggests that exposure indoor was not included in the regression and that matters, it is the important missing piece.
- **Short-term adaptation or avoidance behaviors:** It is possible that some people wore masks or stayed indoors during high pollution episodes (especially after COVID – awareness was higher about masks). These activities chances reduce TB infections and could mute pollution to TB link directly which could be enlightening. On days of severe pollution, the Pakistan authorities at times enforced closure of schools or declared 'smog lockdowns'. The levels of pollution were so high in March that such measures were taken that NASA news suggests happened in the late Oct/Nov 2024. So perhaps crowding also reduced to some extent which could have offset at least some transmission. Although this is speculative, it does show that there is a lot more nuance in real life here, such that pollution might actually correlate with behavioral changes which actually lessen the spread of TB.

Some trends stood out but weren't statistically significant. The area that demonstrates a high TB burden also maps with a high pollution load spatially. The relationship between district mean aerosol ($PM_{2.5}$) levels

ISSN: 3079-3319
Volume: 2,
Issue:(01)
May - Jul, 2025

and total tuberculosis cases across all districts analysed plots positively (~0.3). However, the strength of this correlation is weak due to the limited number of data points. The peak in March for Tuberculosis (TB) and $PM_{2.5}$ may be linked to one another. The coefficient for $NO_2$ was positive but very small and insignificant. Nitrogen dioxide ($NO_2$) issued from traffic is supposed to indicate urban activity and crowding. It's logical given short exposure, the closer you are to traffic, the higher the chance of being affected with TB. But again, the results do not settle the matter; they simply do not rule it out. Existing literature indicates that nitrogen dioxide can acutely influence tuberculosis incidence; however, such effects may not have been observed in this study due to limited temporal variation and the use of aggregated data rather than day-level measures.

The analysis did not show a clear signal that increased environment pollution results in a higher incidence for TB in a duration of five months. This means that during that limited period of time, the environmental risk factors did not have a detectable impact on TB case counts or that the impact was too small relative to other noise to be detected.

For the key result of the study, it is critical to note that air quality does not influence TB at all. It only means that the effect may be subtle and/or lagged and/or confounded. The thesis conclusion acknowledges this, stating: *"None of the four pollutant variables demonstrated statistically significant predictive power… suggesting that while air pollution is a known stressor on respiratory health, its direct influence on TB cases – especially over a short time period – may be limited"*.

## 5. DISCUSSION

### *5.1 Interpreting the Lack of Short-Term Association*

According to the most important finding of the this study, researchers found no evidence of a short-term association between air quality indicators and the incidence of tuberculosis (TB). At first glance, it might seem surprising, considering the extensive literature that links pollution to TB risk. There may be many reasons why this cross-sectional analysis found no effect. This reveals something important about TB's epidemiology as well as the complexities of doing research within environmental health.

1. **Disease Latency and Lag Effects:** TB is an example of a long period of infection before manifestation of disease. A person infected today may not develop active TB for months or years (if at all), unless an event like immune suppression activates latent infection. Consequently, associations between exposure and the outcome, on the one hand, may hide a cause-and-effect relationship that is delayed in time. During the 5-month window, there was a high possibility the TB cases diagnosed resulted from infections acquired much earlier , likely in the previous year or before. If high pollution in 2024 contributed to infections that only manifested as TB disease in 2025, this analysis linking 2025 pollution to 2025 cases would not capture it. Indeed, some global studies have highlighted lagged relationships. Yuan et al. (2025) found $PM_{2.5}$ exposure lagged by around 4–5 months had a significant effect. Another Chinese study (Guo et al., 2024) indicated long-term $PM_{2.5}$ exposure over years increased TB risk. These findings align with the idea that the impact of pollution on TB is cumulative and not immediate. These null result, therefore, does not refute the pollution-TB hypothesis; it likely reflects that the time scale of this analysis was too short relative to TB's incubation. In the context of policy, this means environmental improvements might not yield drops in TB incidence instantly, but could pay dividends over a longer horizon – a point for policymakers to consider in setting expectations.
2. **Dominance of Confounding Factors:** TB incidence in a population is driven by a constellation of factors, including socioeconomic conditions, population density, co-infections (like HIV), healthcare access, and public health interventions. These factors vary widely across Pakistan's districts and can easily overshadow the more subtle influence of environmental quality in a short-term analysis. Faisalabad is a huge city and has a strong DOTS program, which is likely capturing the city's Tuberculosis cases, hence the higher number. Kech is a small town with a small population; there is under-reporting taking place here or just the size of the population could account for the lower case numbers. Any real pollution effect may have been affected or concealed in regression that did not control for these. The model's $R^2$ value was close to zero, indicating minimal explanatory power for tuberculosis incidence. This suggests that variation

ISSN: 3079-3319
Volume: 2,
Issue:(01)
May - Jul, 2025

in TB cases was likely attributable to other factors not included in the model. The TB pattern was most likely dominated by differences caused by socio-demographic. Research backs this claim – poverty, hunger, and overcrowding are classic TB heavyweights. Based on this evidence, Fatima et al. 2025ab determined that socio-economic factors were less important than environmental for ARIs. When evaluating TB cases, socioeconomic status may be most important. According to previous studies, tuberculosis often impacts poor, marginalized groups in Pakistan. It is difficult to attribute risk to whether pollution or poverty is responsible when a community has different exposures to pollution. The inability to control for socioeconomic variables represented a limitation of the study and may have affected the findings. Future research should adopt multivariate multilevel (e.g. hierarchical models or structural equation models) approaches.

3. **3. Measurement Error in Exposure:** Environmental data quality is another issue. Although the most accurate data on pollution on a district level was compiled, it is not reflective of the actual exposure of those who got TB. Several people live both indoors and outdoors, especially in rural areas, or work in micro-environments that have air quality levels that are drastically different to what ambient monitors measure. For example, a farmer burning biomass in an open field could have a high personal smoke exposure not captured by a distant city monitor's reading for $PM_{2.5}$. Conversely, monitors might detect dust storms that people can somewhat avoid by staying inside. The **spatial resolution** of this data (one value for an entire district per day) is coarse and likely leads to nondifferential misclassification of exposure. Such misclassification typically biases associations toward the null – meaning it could make it harder to find a true link even if one exists. Indeed, the thesis acknowledges that averaging AQI and pollutant levels over large areas may "dilute association strength" and potentially "wipe out underlying causal relationships" due to measurement error. In future studies, using finer-grained exposure assessment (e.g. modeling pollution at the neighborhood level, personal air sampling, or time-activity pattern data) could improve detection of an effect. Moreover, integrating indoor air quality data is crucial. If most transmission occurs in poorly ventilated indoor spaces, then metrics like indoor $PM_{2.5}$ or CO2 (as a proxy for ventilation) might correlate with TB risk more strongly. This study didn't directly measure these except via survey questions. The fact that many TB patients reported poor ventilation and high indoor smoke exposure suggests indoor pollution may be a key driver – one that ambient AQI does not capture. Hence, the null result for ambient pollution might mask a positive result for total pollution exposure when indoor is included.

4. **4. Short Observation Period and Statistical Power:** Five-months is short in epidemiology and will probably reduce statistical power to find effects. With around 60 data points (12 districts x 5 months), this critical regression did not have sufficient power to identify what might be a small effect size. This analysis might not have been strong enough to find that given the variability, pollution does raise the incidence of TB by a few percent. A much longer survey over several years (which will create more data points and enable control of year-to-year differences) might reveal a significant relationship. Moreover, although the number of TB cases was relatively high, it showed some stochastic variation due to a few large districts that characterized it. Linear trends may not be observable due to overdispersion in the data. Advanced statistical approaches, such as negative binomial regression for count outcomes or mixed-effects models treating district as a random factor, could potentially extract additional signal; however, their utility is limited with only 12 observational units. The research may not have collected enough data to find subtle pollution effects on the microbiome. An increase in TB incidence of 2% as a result of an increase of 10 $\mu g/m^3$ $PM_{2.5}$, hypothetically speaking, will mean, given the numbers something of the order of 1-2 cases difference in a month for a district – well within random variability. The fact that these findings returned small (and often negative) coefficients is telling. The confidence intervals likely encompassed both moderate negative and moderate positive values, although these were not reported in detail. It means that the data is not definitive

ISSN: 3079-3319
Volume: 2,
Issue:(01)
May - Jul, 2025

evidence of "no impact" but rather the impression of "non impact" has not appeared with current evidence.

5. **Biological Time Window:** Short-term pollution fluctuations may have little impact on TB in the absence of stressors. TB disease progression may consider more long-term cumulative exposure and/or critical windows (e.g., a high exposure at the time of infection or delayed initial latency). For example, a brief rise in $PM_{2.5}$ does not matter unless it fits a long-term pattern of weakening immunity, then this attempt to correlate month-on-month changes with same-month TB may fail for other reasons. The negative coefficients for $PM_{2.5}$ and $PM_{10}$ suggest that months with slightly higher pollution did not coincide with months of increased TB cases, possibly because those cases were initiated in earlier periods, as previously discussed. This relates to the latency point but emphasizes that TB as an outcome might smooth over short-term exposure differences. In contrast, diseases like pneumonia or even COVID-19 might respond more immediately to pollution changes (as some studies have shown, acute respiratory infections can rise within days of smog). TB's insidious progression likely buffers it against short term environmental fluctuations, making it more a function of multi-month or multi-year exposure.

These findings, therefore, align with a cautious interpretation: air pollution is likely an indirect and long-term risk factor for TB rather than a direct short-term trigger. This interpretation is supported in the thesis text, which notes that these results "temper the detectable influence" of pollutants on TB, and that even elevated pollutant levels may not display a significant effect on TB incidence "unless confounding demographic variables are accounted for". In other words, pollution's effect on TB might be real but subtle, requiring careful teasing out.

### *5.2 Comparison with Other Studies and Context*

The lack of short-term association differs from some studies that have reported connections between pollution and TB, but it resonates with others, highlighting a nuanced picture:

- Several **large-scale studies in China** have found positive associations. For instance, Lu et al. (2023) in Nantong, China (Heliyon) observed that higher $PM_{2.5}$ and $PM_{10}$ correlated with increased TB notifications in a time-series from 2015–2019. However, their effect sizes were small and required a longer time frame to establish significance. They also noted temperature modified effects (with stronger association in warmer seasons), suggesting complexity. This study's shorter timeframe and singular seasonal window might have missed such interactions.
- A systematic review in 2019 was done by Yu et al. of all the studies so far undertaken and it was seen that half of them show a significant association between at least one pollutant and TB while the other half do not show a similar relationship. The authors thought most of the heterogeneity was due to differences in the lag periods and background factors. The choice of methodology (cross-sectional versus longitudinal) is very important and these results illustrate that.
- Research in neighbouring nations has also been mixed. Several investigations in India found that TB incidence was higher in districts with higher particulate pollution, although the effect of urbanization muddied the waters. In a case-control study in Delhi, TB patients did not differ from the controls in their pollution exposure. The researchers attributed finding of positive skin test in authors' TB control to that all subject, including controls, to be expose to TB, which is similar to this situation in the big cities of Pakistan. This means that beyond a particular level of pollution, everyone gets exposed, and the variation is inadequate to distinguish risk – in other words, saturation.
- According to surveys from these patients, it seems that indoor factors may be the most important. More than half the patients were exposed to indoor smoke (68% using biomass fuels and poor ventilation –conditions that are known to influence TB very strongly. A WHO report (2007) estimated that half of TB cases in women worldwide could be attributable to indoor air pollution from solid fuels, given their high exposure. If that's the case in this population, ambient pollution might be a smaller slice of the pie. Measures to improve indoor air (clean stoves, better housing) could do more for TB

in Pakistan than ambient air policies, at least for the time being, it suggests.

- These finding that TB peak in March (spring) was in agreement with numerous studies (Fatima et al 2024, Pakistan, etc) which indicate that TB often peaks in spring (starts the epidemic) and troughs (ends the epidemic) in winter in temperate climate. It's thought to be due to vitamin D (low levels in winter reduce immunity, causing cases to show up later) or crowding indoors in winter (losing in spring). In winter, heating and crop burning contribute to pollution peaks in Pakistan. TB peaks are more likely to match with the end-of-winter when there are cold temperatures. This also supports a crowding/immunity theory and not just pollution. This means that the way humans behave and function on a seasonal basis may actually affect TB instead of seasonal pollution practices. It could not be determined whether pollution was a key acute driver of tuberculosis or whether other factors contributed to the observed rise in cases. If pollution had been a primary acute driver, an increase in cases would have been expected in December or January, during the period of most severe smog; however, such a pattern was not observed. The rise in TB was noted after that in February/March, perhaps as a lag phenomenon, or because of some other reason.
- In Pakistan, national TB control has increased treatment coverage but continues to fail to contain transmission in urban slums and remote areas. TB programs have never formally included environmental improvements like sanitation and housing ventilation before. This paper provides current evidence that solely focusing attention on outdoor air pollution is unlikely to lead to immediate reductions in TB. These results show little short-run effect of improved ambient air quality on tuberculosis (TB). This suggests that TB policymakers should not expect a decline in TB incidence just by improving smog conditions over one season. In the long run, air quality improvement plus the addition of other interventions could slowly decrease the baseline susceptibility of the population to TB and other respiratory diseases.

### *5.3 Public Health and Policy Implications*

Even though these results did not show a direct short-term pollution-TB link, there are important implications for public health, urban planning, and policy:

- **Integrating Environmental Surveillance with TB Control:** Information systems that link environmental monitoring (e.g., air quality) with health surveillance activities could provide valuable early warnings. Although the data in this study were compiled manually, an integrated surveillance system that routinely combines air quality metrics with TB notifications would facilitate the early identification of vulnerability hotspots. Health departments, for example, could place maps of TB case clustering beside pollution maps, thereby helping priorities interventions. Although this data did not show a short-term effect, places with chronically high pollution might deserve extra TB screening (since those populations might be under more respiratory stress). Pakistan could enhance its Health Management Information Systems to include environmental exposure indicators for TB patients (e.g., home AQI index or indoor conditions), improving risk factor data for each case.
- **Indoor Air Quality and Housing Interventions:** The lack of ambient effect and literature consensus point strongly to indoor environmental improvements as key TB prevention measures. Efforts such as providing subsidized LPG or efficient cookstoves to households currently using biomass could reduce indoor $PM_{2.5}$ dramatically, potentially lowering TB infection risk for women and children in those homes. Improving ventilation in homes (through simple measures like adding windows, air vents, or fans) could also help disperse infectious droplets. These findings and patient data support allocating resources to such interventions. National TB programs traditionally prioritize diagnosis and treatment; however, collaboration with housing and energy initiatives is necessary to address underlying structural and environmental determinants of disease. For example, Pakistan's government could incorporate TB risk considerations into its "clean cooking" initiatives or urban slum upgrading projects. This aligns with the idea of "health in all policies" –

ISSN: 3079-3319
Volume: 2,
Issue:(01)
May - Jul, 2025

making sure that environmental and housing policies factor in health outcomes like TB.

- **Longitudinal Research and Multi-variable Models:** The findings underscored the need for long-term studies. As a policy implication, funding should be directed to establish cohorts or longer surveillance that track communities' exposure and TB outcomes over years. This will clarify the impact of chronic pollution exposure on TB better than this snapshot could. Also, more complex models including nutrition, diabetes, smoking, etc. should be used – essentially treating TB as a multi-factorial problem. From a policy perspective, that means interventions also need to be multi-pronged: improving air quality alone won't solve TB, but it can complement efforts to improve nutrition, treat co-morbidities, and strengthen health systems.
- **Climate Change Adaptation in TB Control:** While this short-term data didn't show a spike from a dust storm or heatwave, the literature and logic suggest that climate change will indirectly affect TB by altering environmental conditions. For example, more frequent extreme pollution events (wildfire smoke, intense smog) could become triggers for respiratory health crises, potentially including TB flare-ups in vulnerable groups. The policy recommendation is that TB control programs should begin considering climate adaptation – e.g., ensuring continuity of TB services during environmental disasters, and protecting patients (who have compromised lungs) during severe pollution episodes. Moreover, working with climate and environmental sectors to mitigate pollution (like crop residue management to reduce smog) can be seen as co-beneficial for TB and general health.
- **Air Quality Regulation and Awareness:** This research proves that citizens are being exposed to unhealthy levels of air for a long time. The TB effect may take a while to show, but the health impact is big (as burden of disease estimates for air pollution also show). Air quality standards on industrial emissions, vehicular exhaust, and agricultural residue burning require significant strengthening. Measures that reduce respiratory stress are likely to yield broad public health benefits, including reductions in tuberculosis burden. Achieving sustained improvements in air quality would therefore contribute not only to general respiratory health but also to TB control. In addition, greater public awareness of the health impacts of air pollution is essential to support behavioral change and policy enforcement. People can practice protective measures, be it an N95 mask on a heavy smog day, an air purifier if one can afford it, or avoiding outdoor exercise when AQI is high. This is particularly relevant for TB patients and high-risk populations (e.g., those with latent TB or HIV), who should be advised to limit exposure during severe pollution to protect their lungs. Campaigns should link pollution to respiratory health and will, over time, help build support for air cleansing policies in the community.
- **Targeted Interventions in High-Risk Zones:** Although no statistically significant associations were identified, certain districts such as Faisalabad and Peshawar exhibited both high tuberculosis incidence and elevated pollution levels. These may be targeted zones for concentrated areas of intervention. For instance, one can pilot integrated interventions in the slum areas with poor ventilation but high TB in Faisalabad: improving the ventilation of clinics and homes, distributing respiratory masks, concurrently screening for TB and other lung diseases and so on and so forth. GIS mapping (as cited in Fatima 2025a) will help to identify micro-hotspots of environmental degradation and TB overlap so that targeted allocation of resources can be made.
- **Intersectoral Collaboration:** Health and environment sector must break the silo and work hand in hand. COVID-19, TB, and the climate crisis are linked, they impact resources on which human lives depend. The absence of short-term associations does not imply that tuberculosis and environmental factors should be addressed separately. It may mean that the solution requires joint action. Collaboration across several sectors is essential. For example, TB programs that are working with city officials in order to reduce indoor crowding in tenements, or with environmental agencies to ensure sharing data. Integrating environmental officers into tuberculosis task forces, and reciprocally involving TB program personnel in environmental initiatives,

could support more holistic interventions. The UN Sustainable Development Goals (SDGs) are interconnected. Consequently, without progress of SDG 11 (sustainable cities), climate action (SDG 13) and others, TB elimination by 2030 will likely not be achieved.

## 6. CONCLUSION

The study sought to show links between air quality and tuberculosis transmission in vulnerable districts of Pakistan. In doing so, it sheds light on the challenges and necessitates treating TB as an eco-social disease. Across the five-month study period, a substantial tuberculosis burden was recorded (6,285 cases in 12 districts), alongside persistently poor ambient air quality (mean AQI ≈151; $PM_{2.5}$ ≈60 μg/m³). Nevertheless, these analyses found no short-term predictive relation between ambient pollution levels and fluctuations in TB cases. In other words, districts and months with higher measured $PM_{2.5}$, $PM_{10}$, $NO_2$, or AQI did not experience significantly higher TB incidence in that same timeframe. This result suggests that within a short window, the direct impact of ambient air pollution on TB incidence is not readily observable, likely due to TB's long incubation period and the overriding influence of other factors (like socio-economic conditions and indoor exposures). Importantly, this finding does not imply that environmental factors are irrelevant to TB. On the contrary, these extensive literature review and contextual analysis affirm that chronic exposure to polluted air can weaken respiratory defenses and that poor indoor environments facilitate TB spread. The lack of an immediate correlation in this data underscores that TB's response to environmental stressors is complex and delayed. It reinforces the view of TB as not merely a clinical problem but a "barometer" of environmental and social wellbeing. Clean air, adequate housing, and a healthy climate form a foundation upon which biomedical TB interventions can be more effective.

In conclusion, tuberculosis control in Pakistan and similar settings must extend beyond the biomedical paradigm to include environmental health interventions. While this study did not demonstrate an immediate statistical link between air pollution and TB, it emphasizes that creating healthier environments is an investment in respiratory health resilience. Clean air, efficient housing ventilation, and climate adaptation are not traditionally in the TB program toolbox, but they are increasingly recognized as vital components of a comprehensive strategy to end TB as a public health threat. TB, often called a "social disease," is equally an environmental disease – one that thrives in the fumes of urban pollution and the stagnation of poorly ventilated dwellings. Conversely, it wanes where humans enjoy cleaner, more spacious, and more equitable living conditions.

Pakistan, as a high TB burden country with severe air pollution challenges, stands at the intersection of these issues. By tackling environmental determinants and traditional risk factors in tandem, Pakistan can accelerate progress toward its TB elimination goals.

## 7. POLICY IMPLICATIONS

Building on the findings and global best practices, following policy recommendations are proposed for integrating environmental considerations into TB control efforts in Pakistan and similar contexts:

- Strengthen Environmental Health Surveillance: Develop an integrated TB-environment information system that links daily air quality data with TB case reporting.
- Improve Indoor Air Quality and Housing: Launch public health initiatives focused on reducing indoor air pollution and improving household ventilation, as these measures can directly lower TB transmission risk.
- Adopt a Long-Term, Multi-Sectoral Perspective: Recognize that preventing TB requires addressing its upstream determinants.
- Enhance Public Awareness and Behavior Change: Initiate community-focused campaigns about the link between environment and respiratory health. Public service messages can highlight that "clean air is everyone's right and responsibility", making the case that reducing pollution will protect families from TB and other diseases.
- Leverage Technology for Monitoring and Prediction: Invest in modern tools like low-cost air sensors and data analytics (AI) to better understand and predict TB-environment dynamics.
- Global and Regional Collaboration: Finally, situate Pakistan's efforts within the broader international context. Air pollution and TB are transboundary

challenges. Strengthen partnerships with global initiatives like the WHO's End TB Strategy and the Global Fund, advocating for resources that allow environmental interventions as part of TB grants.

By implementing these recommendations, Pakistan can move towards a paradigm where TB prevention is embedded in environmental policy, and environmental health is a fundamental pillar of infectious disease control. The evidence suggests that the greatest gains against TB will come not just from better drugs or diagnostics, but from uplifting the environments in which people live and work. In essence, every unit reduction in $PM_{2.5}$, every household given a ventilated kitchen, every city park created, and every slum upgraded to have proper housing – these are as much TB interventions as are sputum tests and antibiotics. Policymakers should embrace this expansive vision. It promises not only progress toward eliminating TB, but also a healthier, more productive society overall.

## REFERENCES

Alkhanani, M. F. (2025). Predictive modeling of hemoglobin refractive index using Gaussian process regression with interpretability through partial dependence plots. *PLOS ONE, 20*(5), e0324827. https://doi.org/10.1371/journal.pone.0324827

Blount, R. J., Phan, H., Trinh, T., *et al.* (2021). Indoor air pollution and susceptibility to tuberculosis infection in urban Vietnamese children. *American Journal of Respiratory and Critical Care Medicine, 204*(10), 1211–1221.

Dangisso, M. H., Datiko, D. G., & Lindtjørn, B. (2020). Identifying geographical heterogeneity of pulmonary tuberculosis in southern Ethiopia: A method to identify clustering for targeted interventions. *Global Health Action, 13*(1), 1785737. https://doi.org/10.1080/16549716.2020.1785737

Fatima et al. (2024) – GeoJournal – Fatima, M., Butt, I., Firouraghi, N., Khalil, M., & Kiani, B. (2024). Space-time analysis of tuberculosis (2016–2020) in South Punjab, Pakistan. *GeoJournal, 89*(1), 1–13.

Fatima, M., Butt, I., Firouraghi, N., Kiani, B., *et al.* (2025a). Exploring geospatial clusters of five primary respiratory diseases in South Punjab, Pakistan: An epidemiological examination. *Geography, Environment, Sustainability, 18*(1), 14–22.

Fatima, M., Butt, I., MohammadEbrahimi, S., Gruebner, O., *et al.* (2025b). Spatiotemporal clusters of acute respiratory infections associated with socioeconomic, meteorological, and air pollution factors in South Punjab, Pakistan. *BMC Public Health, 25*, Article 469.

Guo, T., Tian, S., Xin, H., *et al.* (2024). Impact of fine particulate matter on latent tuberculosis infection and active tuberculosis in older adults: A population-based multicentre cohort study. *Emerging Microbes & Infections, 13*(1), 2050–2061.

Heliyon – Lu et al. (2023) – Lu, J.-W., Mao, J.-J., Zhang, R.-R., *et al.* (2023). Association between long-term exposure to ambient air pollutants and the risk of tuberculosis: A time-series study in Nantong, China. *Heliyon, 9*(6), e17347.

Ishfaq, M., & Gill, A. R. (2023). Impact of Indoor Air Pollution on Health Outcomes in Pakistan: A Case Study of Multan District. *Pakistan Journal of Humanities and Social Sciences, 11*(2), 1261–1269. https://doi.org/10.52131/pjhss.2023.1102.0431

Kharwadkar, S., Attanayake, V., Duncan, J., Navaratne, N., & Benson, J. (2022). The impact of climate change on the risk factors for tuberculosis: A systematic review. *Environmental Research, 212*(Pt C), 113436. https://doi.org/10.1016/j.envres.2022.113436

Lu, J.-W., Mao, J.-J., Zhang, R.-R., *et al.* (2023). Association between long-term exposure to ambient air pollutants and the risk of tuberculosis: A time-series study in Nantong, China. *Heliyon, 9*(6), e17347. https://doi.org/10.1016/j.heliyon.2023.e17347

Mao, J. J., Zhang, Y., Xia, J. Q., *et al.* (2023). Population impact of fine particulate matter on tuberculosis incidence in China. *BMC Public Health, 23*, Article 16934. https://doi.org/10.1186/s12889-023-16934-8

Mohidem, N. A., Osman, M., Hashim, Z., *et al.* (2021). Association of sociodemographic and environmental factors with spatial distribution of tuberculosis cases in Gombak, Malaysia. *PLOS ONE, 16*(6), e0252146.

Schwalb, A., *et al.* (2024). Subnational tuberculosis burden estimation for Pakistan. *PLOS Global Public Health.* https://doi.org/10.1371/journal.pgph.0003653

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*

ISSN: 3079-3319
Volume: 2,
Issue:(01)
May - Jul, 2025

*Reports, 7*(10), e70130. https://doi.org/10.1002/hsr2.70130

Wang, X., Zhao, Y., Hou, Z., Chen, X., Jiang, S., Liu, W., Hu, X., Dai, J., & Zhao, G. (2023). Large-scale pathway reconstruction and colorimetric screening accelerate cellular metabolism engineering. *Metabolic Engineering, 80*, 107–118. https://doi.org/10.1016/j.ymben.2023.09.009

World Health Organization (WHO). (2007). *Fuel for Life: Household Energy and Health*. Geneva: WHO.

World Health Organization (WHO). (2024). *Global Tuberculosis Report 2024*. Geneva: WHO.

World Health Organization (WHO). (2025). Tuberculosis Fact Sheet – Key Facts (14 March 2025). *WHO Newsroom, Geneva.*

Yuan, D., Xie, B., Pang, Z., Liu, K., & Chen, B. (2025). Short- and long-term exposure to ambient air pollution and greenness in relation to pulmonary tuberculosis incidence. *Scientific Reports, 15*, Article 25594.