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Routine Childhood Immunization Coverage and Tuberculosis Incidence in ASEAN and China: Evidence from a Two-Way Fixed-Effects Panel, 2000–2022

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Abstract

Tuberculosis (TB) incidence remains uneven across ASEAN economies and China, reflecting differences in health-system capacity and broader development conditions. This study examines whether routine immunization performance—treated as a measurable proxy for primary healthcare delivery capacity—is associated with TB incidence over time. Using a balanced country–year panel covering 11 economies from 2000 to 2022 (N = 253), the analysis constructs an Immunization Index as the mean of DPT and measles immunization coverage. The outcome is TB incidence per 100,000 population, estimated in both level and logarithmic forms. The empirical strategy combines descriptive association tests with multivariable panel regressions, including two-way fixed effects (country and year) to account for time-invariant national characteristics and common temporal shocks. In pooled and fixed-effects level models, immunization is negative but not statistically significant. In a two-way fixed-effects log specification, immunization is marginally significant ($\beta = -0.0034$, $p < .10$). The preferred lagged log fixed-effects model indicates a statistically significant delayed association: a one-point increase in the prior-year immunization index is associated with approximately a 0.54% reduction in current-year TB incidence ($\beta = -0.0054$, $p < .01$), implying roughly a 5.26% reduction for a 10-point improvement. Electricity access and internet use are consistently negative and significant in log fixed-effects models, highlighting the role of enabling infrastructure and connectivity. Findings support an interpretation of immunization performance as a system-capacity indicator linked to subsequent reductions in communicable disease burden, while recognizing the observational design and limited number of country clusters.

Keywords: *Tuberculosis incidence; immunization coverage; DPT; measles; panel data; two-way fixed effects; ASEAN; China; health systems capacity; World Development Indicators*

1. Introduction

Tuberculosis (TB) remains a persistent public health and development challenge in many Asian economies. While TB control is often discussed in terms of treatment protocols, diagnostic capacity, and targeted surveillance, TB incidence at the population level is also shaped by broader determinants: the quality and reach of primary healthcare, the reliability of public health delivery systems, and structural conditions that enable prevention, early detection, and continuity of care. For multi-country settings such as ASEAN, these determinants are not uniform. Countries differ widely in baseline disease burden, infrastructure availability, health financing arrangements, and institutional capacity to execute routine public health programs at scale.

Immunization coverage is among the most visible and routinely measured indicators of public health system performance. Unlike episodic interventions, routine immunization requires continuous execution: stable supply chains, functional cold-chain logistics, local outreach, systematic recordkeeping, community trust, and effective coordination between central agencies and front-line services. For this reason, immunization coverage may be interpreted not only as a disease-specific preventive input, but also as a proxy indicator of health system capacity and governance—particularly in contexts where consistent delivery is difficult. If immunization performance reflects the operational capability of primary care systems, it may plausibly relate to other communicable disease outcomes, including TB incidence, through shared pathways such as access, outreach, compliance, monitoring, and program continuity.

At the same time, TB epidemiology has features that complicate simple contemporaneous associations. TB incidence may respond slowly to changes in system performance, and reported incidence can be influenced by improvements in case detection and surveillance quality. Moreover, immunization indicators are likely correlated with

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development measures such as income, sanitation, electrification, and digital connectivity—factors that themselves affect living conditions, access to services, and public health program execution. Consequently, empirical analyses must distinguish descriptive co-movement from more robust within-country associations over time, while controlling for confounding structural conditions and common time shocks.

This study addresses these issues through a country-year panel analysis focusing on ASEAN economies and China over the period 2000–2022. The study constructs an Immunization Index (mean of DPT and measles coverage) to represent routine immunization performance, and examines its association with TB incidence per 100,000 population. The empirical strategy combines descriptive correlation analysis with multivariable panel regressions, including two-way fixed effects (country and year) to absorb time-invariant national characteristics and region-wide temporal shocks. In addition, the study tests a lagged specification to evaluate whether immunization performance predicts TB incidence with a plausible temporal delay, consistent with program transmission mechanisms and reduced simultaneity concerns.

1.1 Objectives of the Study

This study aims to:

a. Describe the structure and completeness of a balanced country–year panel dataset for ASEAN countries and China covering the period 2000–2022, using TB incidence, immunization performance, and selected development and health-system indicators.

b. Examine the pooled and country-specific bivariate associations between the Immunization Index and TB incidence, including the degree of heterogeneity across countries.

c. Estimate the association between immunization performance and TB incidence using multivariable panel regression models that incorporate key controls (income, sanitation, electrification, internet use, and health financing indicators).

d. Assess whether the immunization–TB relationship becomes more coherent when TB incidence is modeled proportionally (log outcome) and when immunization performance is specified with a one-year lag, under a two-way fixed effects framework.

1.2 Background of the Study

Tuberculosis continues to impose a non-trivial burden on public health systems in Asia, including several ASEAN member states. Beyond its direct morbidity and mortality implications, TB incidence serves as an indicator of broader social and institutional conditions: housing and crowding, access to healthcare services, continuity of treatment, the capacity of surveillance systems, and the effectiveness of public health outreach. These determinants are unevenly distributed across the region. While some countries exhibit strong infrastructural foundations and mature public health systems, others face persistent constraints related to service delivery, geographic dispersion, fiscal limitations, and administrative capacity.

A practical challenge in regional health analytics is the identification of measurable indicators that can represent “system strength” in a consistent manner across multiple countries and years. Direct measures of TB program performance (such as treatment adherence, contact tracing quality, diagnostic coverage, and case detection rates) are often incomplete, non-comparable across settings, or unavailable over long time spans. By contrast, routine immunization indicators are widely reported and comparatively standardized, making them attractive for macro-level longitudinal analysis.

Routine immunization coverage—particularly for common childhood vaccines—requires continuous and reliable operational capability: procurement and distribution, cold-chain logistics, data recording and follow-up systems, and community-level engagement. Because these operational requirements overlap with the broader functions of primary care delivery and public health administration, immunization coverage may plausibly reflect a country’s ability to execute programs that also influence TB outcomes. However, such relationships are not guaranteed to be contemporaneous. TB incidence may respond with delay to system-level improvements, and reported incidence may be affected by changes in surveillance intensity or diagnostic expansion. These considerations justify an empirical design that distinguishes descriptive correlation from within-country changes over time and tests lag structures.

Within this context, the present study uses a longitudinal panel of ASEAN countries and China to examine whether immunization performance—operationalized through a composite immunization index—has a measurable association with TB incidence after accounting for structural development indicators (income, sanitation, electrification, and digital connectivity) and health financing measures. The analysis is conducted over a balanced 2000–2022 window to enhance comparability and reduce distortions from inconsistent reporting.

1.3 Conceptual Framework

The conceptual logic of the study is grounded in the view that communicable disease burden is shaped by both proximal public health performance and structural enabling conditions. In this framework, TB incidence is treated as an epidemiological outcome influenced by a system of interacting factors:

1.3.1 Core relationship: Immunization performance as system capacity

The primary explanatory construct is immunization performance, measured by an Immunization Index derived from routine vaccination coverage indicators (DPT and measles). The index is conceptualized not only as protection against specific vaccine-preventable diseases but as a proxy for broader primary healthcare and public health delivery capacity. High immunization performance implies functional outreach systems, reliable logistics, community trust mechanisms, and operational governance—capabilities that can plausibly contribute to reduced TB incidence through indirect pathways such as earlier health-seeking behavior, improved public health monitoring, and stronger local service delivery.

1.3.2 Structural and enabling pathways (controls)

The immunization–TB relationship is embedded within structural conditions that may confound or mediate observed associations:

a. Economic capacity (GDP per capita): reflects household resources, government fiscal capacity, and the ability to finance service delivery and infrastructure.

b. Basic sanitation access: captures environmental and living-condition constraints that affect overall infection vulnerability and public health risk.

c. Electricity access: represents infrastructure enabling service continuity, health facility functionality, and household-level improvements that support effective care delivery.

d. Internet use: reflects connectivity and information access, which may affect health information dissemination, administrative modernization, and service reach.

e. Health financing indicators (Health expenditure as % of GDP; Out-of-pocket share): represent financing structure and potential barriers to healthcare access.

1.3.3 Time dynamics and lag structure

Because improvements in system performance and public health capacity do not always translate immediately into changes in TB incidence, the framework anticipates that immunization performance may exhibit a delayed association with TB outcomes. This motivates the inclusion of a one-year lag of the immunization index in the preferred model, consistent with a system-capacity interpretation and as a partial mitigation of contemporaneous simultaneity.

1.3.4 Empirical implementation: isolating within-country effects

The framework recognizes that countries differ in baseline characteristics that are not fully measured (e.g., geography, long-standing institutional quality, baseline disease ecology). To address this, the empirical model applies country fixed effects to absorb time-invariant differences and year fixed effects to absorb common shocks or region-wide trends. The remaining variation used for inference is primarily within-country change over time, aligned with the conceptual objective of assessing whether improvements in immunization performance correspond to subsequent reductions in TB incidence after controlling for structural conditions.

2. Review of Related Literature

2.1 Immunization Coverage and Tuberculosis Burden: Evidence from BCG and Ecological Studies

Research shows mixed evidence on the correlation between childhood immunization coverage, particularly BCG vaccination, and tuberculosis (TB) incidence at the population level. In Japan, despite high BCG coverage (~97%), childhood TB incidence declined but was associated more with age and vaccination history than changes in immunization policy, suggesting complex factors beyond coverage alone (Hamaguchi et al., 2025). In

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Brazil and Indonesia, declines in BCG coverage below 90% were linked to rises or spatial clustering of pediatric TB cases, highlighting the importance of maintaining high vaccination rates alongside other public health measures (Carvalho et al., 2025; Brillianti & Hendrati, 2022). However, some ecological studies found positive correlations between higher BCG coverage and increased child TB incidence, possibly reflecting confounding factors like population density or reporting differences rather than a direct causal relationship (Prameswari & Hendrati, 2024; Nugraha & Setiyadi, 2025). A large individual participant data meta-analysis confirmed that infant BCG vaccination significantly protects children under 5 years from developing TB but shows limited effectiveness in older children and adults, emphasizing age-specific vaccine impact rather than simple country-level correlations (Martinez et al., 2022). Overall, while high childhood immunization coverage is crucial for reducing TB risk in young children, cross-country or panel studies indicate that multiple contextual factors influence observed TB incidence trends at the macro level.

2.2 Routine Immunization as a Proxy for Primary Health Care and Health-System Capacity

Routine immunization coverage is widely validated as a proxy indicator for the strength and functionality of primary healthcare (PHC) systems. The successful delivery of vaccines depends on a constellation of system components: a competent health workforce, robust supply chains, functional data systems, community trust, and effective governance. Therefore, gains in immunization coverage signal improvements across these interconnected domains (Blanc et al., 2022). For instance, empirical work in Nigeria demonstrates that the quality of management and governance at the PHC level directly influences DTP3 coverage, reinforcing that immunization performance is an outcome of organizational capacity (Begha, 2023). Similarly, the structural organization of health services, such as the integration of preventive care in well-baby clinics, correlates with more equitable vaccine uptake and serves as a marker of system functionality (Arat et al., 2019; Valdecantos et al., 2025). This foundational capacity is itself dependent on the integrity of the health professions education pipeline; challenges such as faculty burnout, clinical placement scarcity, and generational shifts directly undermine the development of a resilient and competent workforce, thereby constraining the very system that immunization metrics seek to measure (Bermido et al., 2025). Systematic reviews further emphasize that political commitment, clear governance, and multi-stakeholder collaboration are essential for program success, while persistent service delivery and workforce constraints limit performance (Amponsah-Dacosta et al., 2020; Bangura et al., 2020; Blanc et al., 2022). The practical interface between public health reforms and private sector capacity is evident in the Philippines, where the adaptation of dominant retail pharmacy chains to Universal Healthcare has become a test of accessibility and service delivery beyond government facilities alone (Atento & Atento, 2025). Consequently, employing an ImmunizationIndex as a system-capacity indicator is conceptually sound: it captures the multidimensional nature of PHC strength—governance, delivery, and access—that single metrics cannot reflect (Amponsah-Dacosta et al., 2020; Begha, 2023; Blanc et al., 2022). The coherence and integrity of these governance structures, as emphasized in frameworks linking domestic governance to policy credibility, are foundational to reliable system performance and public trust (Atento, 2025; Atento et al., 2025b; Bangura et al., 2020).

2.3 Lagged and Cumulative Effects of Immunization Programs on Infectious Disease Outcomes

The impact of public health interventions, including immunization programs, is rarely instantaneous. Long-term surveillance and modeling studies consistently demonstrate that reductions in infectious disease incidence follow improvements in program coverage with a considerable lag, often spanning years or even decades. In China, the integration of vaccines into the Expanded Program on Immunization (EPI) led to substantial declines in diseases like pertussis and measles, but these reductions were gradual, unfolding over decades and reflecting the cumulative effect of sustained program scale-up rather than an immediate policy shock (Pan et al., 2021). Similar patterns are observed in Italian data, where post-vaccination declines in disease incidence were persistent and progressive, best modeled by projecting counterfactual trends from the pre-vaccination era (Pezzotti et al., 2018). Global modeling of 50 years of EPI vaccination reinforces this view, showing that reductions in child mortality accumulate progressively across birth cohorts, extending the benefits of immunization well beyond the initial rollout (Shattock et al., 2024; Pezzotti et al., 2018).

These modeled outcomes align with core epidemiological principles: as population-level immunity increases and transmission chains are interrupted, the health gains accrue over time, producing cohort-level benefits that are delayed but substantial (Pan et al., 2021; Shattock et al., 2024). Consequently, specifying lagged effects in analyses of immunization program impacts on infectious disease outcomes is not merely a methodological preference but a conceptual and empirical necessity, as contemporaneous associations may underestimate or obscure the true program effect (Pan et al., 2021; Pezzotti et al., 2018; Shattock et al., 2024). This logic of evaluating delayed intervention effects extends beyond vaccinology, with fields like environmental health using post-rehabilitation biomonitoring of bioindicators to assess the sustained, downstream impacts of cleanup efforts, illustrating a broader methodological precedent for lagged impact evaluation (Ylagan et al., 2025; Pan et al., 2021).

2.4 Structural Determinants of TB: Infrastructure, Sanitation, and Connectivity as Contextual Controls

Tuberculosis is a disease of poverty and social disadvantage, making the inclusion of structural and infrastructural controls essential for any credible macro-level analysis. Indicators such as access to electricity, improved sanitation, and internet connectivity are not merely development amenities; they are proxies for the social determinants of health that shape TB transmission, diagnosis, and treatment outcomes. Strong health systems, characterized by effective service delivery and governance, are significantly associated with lower TB mortality, while environmental factors like air quality also play a role (Wolde et al., 2025). Improved sanitation and urbanization, often correlated with broader infrastructure development, are linked to lower rates of multidrug-resistant TB globally, highlighting the role of well-managed environments in disease control (Wang et al., 2025). Regional disparities in TB burden within large countries like China and Brazil are closely tied to variations in socioeconomic development, PHC coverage, and living conditions, all of which encompass infrastructure quality (Cortez et al., 2021; Zhang et al., 2022; Wolde et al., 2025). These factors operate by shaping proximal risks: crowding facilitates transmission, poor nutrition compromises immunity, and limited access to care delays treatment. Empirical work on child nutrition within the ASEAN region, for example, routinely includes macroeconomic and labor-market indicators as contextual controls because purchasing power and employment structures shape household food security and caregiving environments, which in turn affect child health (Quinto & Atento, 2025; Wang et al., 2025). Therefore, infrastructure indicators are critical covariates in TB models, serving as proxies for the broader social and environmental conditions that determine a population's risk and a health system's capacity to manage disease, thereby preventing the attribution of TB declines to immunization alone when they may reflect wider structural improvements (Cortez et al., 2021; Wang et al., 2025; Zhang et al., 2022).

2.5 Why Fixed-Effects Panel Models Matter: Isolating Within-Country Associations Over Time

To rigorously test the association between within-country improvements in immunization and subsequent changes in TB burden, a methodological approach that controls for time-invariant confounding is essential. Fixed-effects (FE) panel models provide this capability by focusing exclusively on variation within units (e.g., countries) over time, thereby differencing out all unobserved, time-constant heterogeneity that could bias estimates in pooled cross-sectional analyses. While pooled models capture both cross-sectional and temporal variation, they are vulnerable to confounding from omitted variables that differ across countries, potentially inflating or distorting associations. However, model specification requires care. Two-way FE models that simultaneously include unit and time fixed effects can, in some cases, produce estimates that are difficult to interpret or are statistically unidentified (Kropko & Kubinec, 2020). One-way FE models, focusing on either individual or time effects, offer clearer interpretation by cleanly separating within-unit changes from cross-sectional differences (Fernández-Val & Weidner, 2018; Kropko & Kubinec, 2020). Furthermore, conventional FE models typically assume that the effect of a predictor is the same for all units. When this assumption is violated—for instance, if the impact of immunization on TB varies by a country's health system maturity—more flexible specifications are needed to avoid biased estimates (Rüttenauer & Ludwig, 2019; Kropko & Kubinec, 2020). The justification for using FE models is therefore strong: they control for time-invariant confounders and absorb common temporal shocks, helping to isolate the within-unit signal and explaining why pooled correlations often diverge from estimates derived from temporal variation (Bell et al., 2018; Kropko & Kubinec, 2020; Rüttenauer & Ludwig, 2019). The fundamental limits of cross-sectional, correlational designs in establishing causality are well documented; they can reveal co-occurrence but not the direction or mechanism of an effect (Bell et al., 2018; Kropko & Kubinec, 2020). Just as quantitative panel methods require robust specification to avoid biased estimates, qualitative and interpretive approaches in health research underscore that methodological choices are not neutral; frameworks such as narrative health analytics demonstrate that the way

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data is collected, interpreted, and governed—with attention to empathy, ethics, and cultural context—fundamentally shapes the validity and applicability of research findings (Atento et al., 2025c). Studies of environmental contaminants and antimicrobial resistance, for instance, explicitly acknowledge that their correlational designs cannot support causal claims, underscoring the need for panel or quasi-experimental approaches to strengthen inference (Nacino & Basit, 2025; Rüttenauer & Ludwig, 2019).

2.6 Synthesis of the Literature

Across the reviewed literature, three consistent propositions emerge that jointly motivate the present ASEAN–China panel design. First, immunization coverage is repeatedly treated as more than a vaccine-specific input; it functions as a measurable indicator of public health delivery capability. Routine immunization performance reflects the reliability of supply chains, cold-chain logistics, workforce reach, local outreach systems, recordkeeping, and community trust—operational features that are also central to communicable disease control beyond vaccine-preventable illnesses. Consequently, immunization coverage is widely interpreted as a proxy for primary health care functionality and governance capacity, particularly in multi-country contexts where direct, comparable measures of system performance are difficult to obtain over long time spans.

Second, evidence linking immunization and TB outcomes is mixed when evaluated at macro levels, especially when the literature relies heavily on BCG-focused or child TB–oriented designs. Individual-level syntheses and cohort evidence support protective effects of early-life vaccination against TB risk in young children, but ecological or country-level associations may not track cleanly because TB incidence is shaped by multiple interacting forces: socioeconomic conditions, crowding and living environments, treatment continuity, diagnostic and surveillance intensity, and broader reforms in health systems. This mixed evidence is not a contradiction so much as an indication that macro-level TB trends cannot be reduced to any single intervention or coverage rate without accounting for context and confounding structural factors.

Third, both empirical surveillance studies and long-horizon models indicate that improvements in public health programs often manifest as delayed and cumulative population-level impacts rather than immediate contemporaneous changes. This logic supports the inclusion of lag structures when evaluating the association between immunization performance and TB incidence, particularly where improvements in service delivery could affect TB through pathways that plausibly unfold over time (e.g., outreach and access, earlier engagement with care systems, improved administrative continuity, or better integration of primary health services). In addition, the literature consistently indicates that infrastructure and development conditions—sanitation, electricity access, and connectivity—are closely tied to health outcomes and are therefore essential covariates in TB models to avoid attributing to immunization what may reflect broader structural improvements.

Taken together, the literature supports an analytical approach that (a) operationalizes immunization performance using consistently reported routine coverage indicators, (b) models TB burden in a way that improves interpretability across heterogeneous baseline levels (often motivating proportional/log specifications), (c) applies fixed-effects panel methods to control for time-invariant country differences and common time shocks, and (d) tests lagged specifications consistent with delayed program effects. This synthesis provides the conceptual and empirical justification for examining whether within-country improvements in routine immunization performance are associated with subsequent reductions in TB incidence across ASEAN economies and China after conditioning on structural and financing controls.

2.7 Research Gaps

Despite the breadth of research on immunization systems and TB epidemiology, several gaps remain that justify a two-way fixed-effects panel analysis for ASEAN countries and China over 2000–2022.

Gap 1: Limited panel evidence linking routine (non-BCG) immunization performance to TB incidence in multi-country Asian settings.

Much of the immunization–TB literature emphasizes BCG coverage and pediatric TB risk, while fewer studies operationalize routine immunization performance (e.g., DPT and measles coverage) as a system-capacity proxy and relate it to aggregate TB incidence at the country level. This creates an evidence gap for studies that treat routine immunization as an indicator of health-system delivery strength rather than as a TB-specific biomedical exposure.

Gap 2: Insufficient use of designs that isolate within-country change rather than cross-country differences.

Cross-sectional and ecological correlations often blend between-country heterogeneity (baseline development, institutions, reporting systems) with within-country improvements over time. Without fixed effects, estimated associations can be dominated by stable country characteristics. There remains a need for models that explicitly exploit within-country variation, absorbing time-invariant national attributes and common temporal shocks to strengthen interpretability.

Gap 3: Under-testing of lag structures consistent with delayed program impacts and reduced simultaneity.

While immunization and broader public health improvements are frequently understood as producing cumulative effects, many empirical studies still emphasize contemporaneous relationships. TB incidence and its reporting can respond slowly or can be influenced by changes in case detection and surveillance intensity. Explicit lag specifications are therefore required to test whether immunization performance predicts TB incidence with a plausible delay and to reduce concerns that contemporaneous associations primarily reflect measurement or reporting dynamics.

Gap 4: Fragmented integration of structural determinants as controls within immunization–TB models.

The literature recognizes the relevance of sanitation, electrification, and connectivity to disease risk and system performance, but studies vary widely in which structural controls are incorporated and how consistently they are measured across countries and years. A harmonized seeing-through of these infrastructure and development factors within a single panel framework remains limited for the ASEAN–China setting.

Gap 5: Limited evidence based on balanced, comparably measured regional panels over a stable analysis window.

Multi-country health panels frequently face missingness that induces shifting samples across models and years. Few studies explicitly justify a stable analysis window and indicator selection based on completeness rules while retaining key comparators (including large economies such as China and core ASEAN members). A balanced panel approach enhances comparability across specifications and supports clearer interpretation of model changes (levels vs logs; contemporaneous vs lagged).

Addressing these gaps, the present study constructs a balanced ASEAN–China panel (2000–2022), operationalizes routine immunization performance through a parsimonious index derived from consistently reported coverage indicators, and estimates associations with TB incidence using two-way fixed effects, controls for structural and financing conditions, and a lagged immunization specification aligned with delayed program effects.

3. Materials and Methods

3.1 Research Design and Analytical Framework

This study adopts a quantitative, comparative, panel-based design using country-year observations to examine the association between immunization coverage and infectious disease burden in China and selected ASEAN member states. The analytical framework treats immunization coverage as an indicator of preventive public health reach and routine service delivery, and evaluates its relationship with epidemiological burden as reflected by tuberculosis incidence. To improve interpretability and reduce omitted-variable bias, the analysis incorporates controls representing macroeconomic development, living conditions, service access, and health financing structure. The Philippines is treated as a focal benchmark for comparative interpretation within the regional panel.

3.2 Data Source and Data Extraction

All variables were sourced from the World Bank's World Development Indicators (WDI) database and compiled into an annual country-level dataset. WDI was selected due to its standardized indicator definitions, cross-country comparability, and longitudinal coverage. Extraction was conducted at the indicator level, then merged into a unified panel keyed by country and year.

3.3 Study Sample: Countries and Baseline Time Window

3.3.1 Country Coverage

The baseline sample includes 11 countries: Brunei Darussalam, Cambodia, China, Indonesia, Lao PDR, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Viet Nam. During cleaning, Hong Kong, Macau, and Timor-Leste were excluded due to persistently limited data coverage across the candidate indicators and years, which would have produced unstable and highly incomplete country-year panels.

3.3.2 Baseline Time Window (2000–2022)

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The baseline analytic window is 2000–2022. This window was selected to preserve multi-country comparability while retaining key health financing indicators (current health expenditure and out-of-pocket share) that exhibit reporting lags in later years. Indicators that remain available beyond 2022 were not extended to 2023–2024 in the baseline model because doing so would materially increase missingness in the health financing block and induce non-random sample changes across countries.

3.4 Variables and Operational Definitions

3.4.1 Dependent Variable: Epidemiology Domain (TB Incidence)

The core epidemiology outcome is *Incidence of tuberculosis (per 100,000 people)*

This indicator is used as the primary disease-burden measure due to its broad cross-country coverage and substantive relevance as a major infectious disease burden proxy that remains consistently tracked across the study countries.

3.4.2 Independent Variable: Immunization Domain (Immunization Index)

Immunization coverage is operationalized using two WDI childhood vaccination coverage indicators for ages 12–23 months:

a. Immunization, DPT (% of children ages 12–23 months)

b. Immunization, measles (% of children ages 12–23 months)

To produce a parsimonious immunization construct and reduce redundancy from highly correlated vaccine coverage measures, the study computes an Immunization Index for each country-year as the simple arithmetic mean of DPT and measles coverage:

$$\text{ImmunizationIndex}_{it} = \frac{\text{DPT}_{it} + \text{Measles}_{it}}{2}$$

This approach preserves interpretability in percentage-point units and yields a single immunization-domain metric for baseline estimation.

3.4.3 Control Variables

To address confounding and improve comparability across heterogeneous economies and health systems, the baseline model includes the following controls:

Economic development

a. GDP per capita (current US$)

b. Living conditions and basic services

c. People using at least basic sanitation services (% of population)

d. Access to electricity (% of population)

e. Individuals using the Internet (% of population)

Health financing

a. Current health expenditure (% of GDP)

b. Out-of-pocket expenditure (% of current health expenditure)

These controls were selected because they plausibly influence both immunization performance and disease burden through infrastructure, public health investment, service access, and household capacity to absorb health costs.

3.5 Data Cleaning, Harmonization, and Completeness Screening

3.5.1 Harmonization and Panel Construction

Indicator series were merged into a unified dataset using country identifiers and year. Data were inspected for duplicates, inconsistent country naming conventions, and structural missing blocks (e.g., entire indicator series absent for certain countries). All variables were retained in their native WDI units; no rescaling was applied beyond index construction.

3.5.2 Completeness Rule (≥80%) and Rationale

Because sparse country-year coverage can create unstable associations and induce implicit sample selection, the study applies a completeness threshold during variable screening. For baseline inclusion, indicators were required to meet a minimum standard of longitudinal availability across countries, operationalized as ≥80% non-missing annual observations per country over 2000–2022, while maintaining the baseline ASEAN coverage (including Singapore and Viet Nam).

Indicators failing this criterion in ways that would fragment the ASEAN panel or substantially reduce the estimation sample were excluded from baseline models and, where conceptually relevant, moved to robustness modules.

3.5.3 Excluded Indicators (Baseline)

Based on the cleaning audit and completeness checks:

a. Physicians (per 1,000 people) was excluded due to severe sparsity across the ASEAN panel, which would substantially reduce usable observations and distort comparative inference.

b. Hospital beds (per 1,000 people) was excluded from baseline controls because it would require dropping key ASEAN members (notably Singapore and Viet Nam) or shortening the panel further; it is reserved for reduced-coverage robustness checks.

c. HIV incidence indicators were excluded from the baseline epidemiology domain due to structural missingness for China (and other countries), which conflicts with the study's comparative design that requires China in the baseline panel.

3.6 Statistical Analysis Plan

3.6.1 Descriptive and Comparative Analysis

The analysis begins with descriptive profiling of all baseline variables for each country over 2000–2022. This stage emphasizes:

a. Philippines-versus-peers comparisons (ASEAN and China) for immunization coverage and TB incidence.

b. Cross-country dispersion and trends, including identification of periods of convergence/divergence in immunization and TB incidence.

Country-level time series summaries and cross-sectional snapshots (selected years) may be presented to clarify regional contrasts.

3.6.2 Bivariate Association (Correlation)

A correlation analysis is conducted between the Immunization Index and TB incidence to provide an initial, model-free characterization of direction and strength of association. Where correlations are reported, the associated sample size and missingness handling approach are disclosed to avoid overinterpretation.

3.6.3 Multivariate Baseline Model

The core association is estimated using a panel regression framework:

$$\text{TBIncidence}_{it} = \beta_0 + \beta_1 \text{ImmunizationIndex}_{it} + \gamma' \mathbf{X}_{it} + \varepsilon_{it}$$

where $\mathbf{X}_{it}$ includes GDP per capita, sanitation, electricity access, internet use, current health expenditure (% of GDP), and out-of-pocket share.

To address serial correlation and heteroskedasticity common in country panels, inference should use robust standard errors (e.g., heteroskedasticity-robust or clustered by country, depending on final implementation). If fixed effects are used (country and/or year), they are explicitly stated and justified as controlling for time-invariant country characteristics and common shocks.

3.6.4 Treatment of Skew and Scale (Optional Sensitivity)

Because TB incidence and GDP per capita can be skewed, an optional sensitivity specification may apply log transforms (e.g., $\log(\text{TBIncidence})$, $\log(\text{GDPpc})$) to test whether results are robust to scale normalization. Such transformations are treated as sensitivity checks and reported as such.

3.7 Robustness and Sensitivity Analyses (Pre-Specified)

To demonstrate that baseline findings are not artifacts of a particular indicator set or sample definition, the following robustness models are implemented:

3.7.1 HepB3 Immunization Robustness (Excluding Cambodia)

HepB3 is included as an additional immunization indicator in an extended immunization-domain specification. Because Cambodia fails the ≥80% completeness criterion for HepB3, this robustness model is estimated on a reduced country set excluding Cambodia, and is reported separately from the baseline.

3.7.2 Malaria Incidence Robustness (Nine-Country Subpanel)

The epidemiology outcome is replaced with malaria incidence as an alternative infectious disease burden measure. Because malaria incidence is structurally missing for Brunei and Singapore, this robustness analysis is run on a nine-country subpanel excluding Brunei and Singapore, explicitly labeled as reduced-coverage and interpreted cautiously as complementary rather than primary.

3.7.3 Hospital Beds as Capacity-Control Robustness (Reduced Coverage / Shorter Window)

Hospital beds (per 1,000) is introduced as a health-system capacity control in a separate robustness specification. This model is explicitly

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labeled as reduced-coverage and may require a shorter time window and/or reduced country set depending on availability. Its purpose is to test whether the baseline immunization–TB association is sensitive to the inclusion of a capacity proxy that is not viable in the full baseline ASEAN panel.

3.7.4 Exclusion of Physicians

Physicians per 1,000 is not used in baseline or robustness models due to severe sparsity and the resulting risk of biased cross-country comparisons.

3.8 Assumption Checks and Reporting Conventions

Model diagnostics include checks for multicollinearity among controls (particularly among development and infrastructure proxies), residual patterns, and influential observations. Results are reported with coefficient estimates, robust standard errors, p-values, and appropriate goodness-of-fit metrics. The final write-up explicitly documents changes in sample size caused by robustness specifications (reduced-country or reduced-year panels).

3.9 Software and Reproducibility

Data cleaning and analysis are implemented using reproducible scripts and versioned datasets. The final dataset is retained as an auditable artifact, and all derived variables (including the Immunization Index) are generated using documented formulas to ensure replicability.

4. Results and Discussion

4.1 Panel structure, coverage, and data completeness

The baseline analytic dataset is a balanced country–year panel covering 11 economies (ASEAN plus China, after exclusions due to limited data availability) for the period 2000–2022, yielding N = 253 observations (11 countries × 23 years). Each country contributes 23 annual observations, ensuring consistent comparability across specifications.

Only two missing values were detected in the control variable Internet_use (Cambodia 2018; Myanmar 2000). These were imputed using a minimal procedure—within-country interpolation for internal gaps and edge filling for boundary gaps—preserving the balanced panel for regression estimation. The imputed values were 42.6031 (Cambodia, 2018) and 0.000289 (Myanmar, 2000).

4.2 Descriptive statistics of core variables

Table 1 reports pooled descriptive statistics for the baseline variables over 2000–2022 (N=253). The ImmunizationIndex is operationalized as the mean of DPT and measles immunization coverage rates (percentage points). The epidemiological outcome is TB incidence per 100,000 population, analyzed in both levels and logarithmic form (ln_TB) depending on model specification.

Across the pooled sample, ImmunizationIndex averaged 87.62 (SD 12.37), while TB incidence averaged 254.28 per 100,000 (SD 182.92), indicating substantial dispersion consistent with heterogeneous epidemiological conditions and development trajectories across the region. GDP per capita and foundational infrastructure indicators (sanitation, electricity, internet access) also show wide ranges, supporting the use of multivariable and fixed-effects strategies in subsequent analyses.

4.3 Bivariate association patterns: pooled and country-specific

Table 2 presents pooled Pearson correlations among the main constructs. The pooled correlation between ImmunizationIndex and TB incidence is r = −0.504, indicating a moderate negative association in the pooled country-year sample. However, pooled correlations combine between-country differences and within-country over-time movement, and are therefore interpreted as descriptive rather than causal.

To assess heterogeneity, Table 3 reports country-level correlations computed within each country over 2000–2022. The immunization–TB relationship is not uniform: several countries show strong negative correlations (e.g., China r = −0.891; Cambodia r = −0.801; Lao PDR r = −0.753; Philippines r = −0.652), while others are near zero or positive (e.g., Viet Nam r = +0.199). The Philippines' within-country correlation is r = −0.652, consistent with negative co-movement between immunization performance and TB incidence across the period, although this remains correlational.

4.4 Multivariable panel regression results

Table 4 reports four regression specifications that progressively strengthen identification and interpretability:

- **a. M1:** pooled OLS (TB in levels) with country-clustered SE
- **b. M2:** two-way fixed effects (TB in levels) with country-clustered SE
- **c. M3:** two-way fixed effects (ln TB) with country-clustered SE
- **d. M4:** two-way fixed effects (ln TB) with **1-year lagged immunization** (HC1 robust SE)

Key findings:

1. Immunization is not statistically significant in level specifications (M1–M2).

   - M1: ImmunizationIndex β = −0.6434 (SE 3.3552), not significant.
   - M2: ImmunizationIndex β = −0.8317 (SE 1.1252), not significant.

2. In the log-outcome fixed-effects model (M3), immunization becomes marginally significant and interpretable as a semi-elasticity.

   1. M3: ImmunizationIndex β = −0.0034 (SE 0.0020), $p < .10$.
      Interpretation: a 1-point increase in immunization is associated with ~0.34% lower TB incidence (within-country over time, net of country/year effects and controls).

3. The strongest immunization evidence appears in the lagged log FE model (M4).

   2. M4: ImmunizationIndex_L1 β = −0.0054 (SE 0.0012), $p < .01$.
      Interpretation: a 1-point increase in last year's immunization index is associated with ~0.54% lower TB incidence this year; a 10-point increase corresponds to ~5.26% lower TB incidence $exp(-0.0054 \times 10) - 1$.

4. Infrastructure/connectivity controls are consistently negative and statistically significant in the log FE specifications.

   3. M3: Electricity_access β = −0.0056 (SE 0.0024), p < .05; Internet_use β = −0.0068 (SE 0.0026), *p < .01.
   4. M4: Electricity_access β = −0.0055 (SE 0.0010), *p < .01; Internet_use β = −0.0061 (SE 0.0011), *p < .01.

Interpretation (M4): a 10-point increase in electricity access corresponds to ~5.35% lower TB incidence, and a 10-point increase in internet use corresponds to ~5.92% lower TB incidence, holding constant controls and fixed effects.

5. Model fit increases sharply once fixed effects and log transformation are used. R^2 rises from 0.625 (M1) to 0.963 (M2) and to 0.985–0.989 (M3–M4), reflecting the explanatory contribution of country and year effects and proportional modeling of TB incidence.

4.5 Summary of empirical evidence

Taken together:

The immunization–TB relationship is descriptively negative at the pooled level (r = −0.504) and strongly negative in several countries (e.g., China, Cambodia, Lao PDR, Philippines), but heterogeneous across the region.

In multivariable panel regressions, the immunization effect is not robust in levels, becomes weakly detectable in the log FE model, and becomes clearly significant when lagged (M4), consistent with a delayed association.

Electricity access and internet use show stable negative associations with TB incidence in the fixed-effects log models, suggesting that broader system capacity and development factors co-move with reductions in communicable disease burden.

4.6 Discussion of Findings

The empirical findings present a coherent but nuanced picture of how immunization performance relates to tuberculosis (TB) incidence across ASEAN countries and China during 2000–2022. At the descriptive level, the dataset exhibits a moderate negative pooled association between the ImmunizationIndex and TB incidence (r = −0.504, Table 2), suggesting that higher immunization coverage tends to coincide with lower TB incidence when pooling countries and years. However, the country-level correlations reveal substantial

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heterogeneity (Table 3): some countries show strongly negative within-country correlations (e.g., China −0.891, Cambodia −0.801, Lao PDR −0.753, Philippines −0.652), while others are weakly negative, near zero, or even positive (e.g., Viet Nam +0.199). This dispersion indicates that "immunization performance" is not a universally consistent predictor of TB incidence across contexts, and that pooled descriptive patterns likely conflate multiple mechanisms—structural differences between countries and joint improvements over time in health systems, infrastructure, and social conditions.

Reconciling descriptive correlations with multivariable regression results

The regression sequence (Table 4) clarifies why the descriptive correlation does not translate uniformly into a strong contemporaneous multivariable association. In the levels models (M1 pooled; M2 two-way fixed effects), the immunization coefficient remains negative but statistically non-significant (M1: $\beta = -0.6434$; M2: $\beta = -0.8317$). Two interpretive points follow.

First, levels specifications can be dominated by scale effects: countries with high TB burdens and large structural constraints contribute disproportionate absolute variation to the outcome. Second, immunization coverage in many countries is relatively high and changes slowly over time; once controls and fixed effects are included, the remaining within-country identifying variation in the immunization index may be insufficient in a levels framework to yield a stable estimate. In effect, the levels models suggest that "immunization coverage measured in absolute TB cases per 100,000" is not the most informative scale for isolating incremental effects in a region characterized by sharp baseline differences.

This changes when the outcome is modeled proportionally. In M3 (two-way fixed effects with ln TB), the immunization coefficient becomes negative and marginally significant ($\beta = -0.0034$, $p < .10$). In semi-elastic terms, this corresponds to approximately a 0.34% reduction in TB incidence for each 1 percentage-point increase in the immunization index, within countries over time after controlling for both country and year effects and the included covariates. Although the statistical strength is modest, the shift from non-significance in levels to detectability in logs supports a central methodological inference: the immunization–TB relationship is better captured as a proportional association rather than an absolute one.

Why the lagged model is empirically strongest

The most important inferential pivot is M4, where immunization is lagged by one year in the two-way fixed effects log framework. Here, ImmunizationIndex_L1 is negative and statistically significant ($\beta = -0.0054$, $p < .01$), implying that a 1 percentage-point increase in last year's immunization index is associated with approximately a 0.54% reduction in current-year TB incidence (in proportional terms). A more policy-meaningful scaling is a 10-point improvement in immunization performance, which corresponds to roughly a 5.26% reduction in TB incidence in the following year.

There are at least two reasons why this lagged specification produces the clearest signal. Conceptually, improvements in immunization coverage may proxy broader improvements in primary healthcare outreach, logistics reliability, community engagement, and system governance—capabilities that may influence TB control through pathways that plausibly operate with delay (e.g., improvements in contact tracing, timely referral, preventive services, and program compliance). Methodologically, lagging the immunization index reduces immediate simultaneity concerns, where health system changes affecting TB detection or reporting could contemporaneously move both TB incidence estimates and coverage metrics. The lagged result does not establish causality, but it strengthens the plausibility of the directionality and reduces the likelihood that the immunization coefficient is merely capturing contemporaneous noise or reporting artifacts.

Interpreting the role of infrastructure and connectivity

A consistent theme across the best-performing models is the importance of infrastructure and connectivity. Electricity access is negative and statistically significant in M1 and M2 (levels) and remains negative and significant in M3 and M4 (log fixed effects). In M4, the coefficient ($\beta = -0.0055$, $p < .01$) implies that a 10 percentage-point improvement in electricity access is associated with approximately a 5.35% reduction in TB incidence, ceteris paribus. Similarly, Internet use becomes consistently negative and strongly significant in the log FE models (M3: $\beta = -0.0068$, $p < .01$; M4: $\beta =$

−0.0061, $p < .01$). This pattern suggests that TB incidence is strongly linked with broad development and "system capacity" indicators that reflect household living conditions, information access, service reach, and administrative competence.

Two interpretations should be handled carefully. One view is that electricity and internet access are not merely "controls" but are substantive determinants that capture the structural conditions under which TB transmission and control occur. An alternative view is that they may function as proxies for correlated reforms (urbanization, economic restructuring, improvements in surveillance and diagnostic access, or healthcare delivery modernization). In either case, the stability of their coefficients across specifications indicates that TB incidence is embedded in a broader socioeconomic infrastructure context, and immunization operates within that same context rather than in isolation.

GDP per capita and the conditional development signal

The GDP per capita coefficient is strongly significant only in the pooled levels model (M1) and becomes significant again in the lagged log FE model (M4) (ln_GDPpc: $\beta = -0.0814$, $p < .05$). Because both GDP per capita and TB incidence are logged in M4, the coefficient is interpretable as an elasticity: proportional increases in income are associated with proportional reductions in TB incidence. This is consistent with the general expectation that rising economic capacity supports improved nutrition, housing quality, health access, and program financing. Yet the inconsistency across models suggests that GDP effects are partly absorbed by fixed effects and correlated infrastructure variables, and that the "income-to-TB" pathway may be mediated by specific service-delivery capabilities rather than income alone.

Explaining heterogeneity across countries

The heterogeneity evident in Table 3 underscores that regional generalizations should be cautious. A strong negative immunization–TB correlation in one country may reflect synchronized improvements across multiple health domains, whereas near-zero or positive correlations may reflect divergent trajectories in TB surveillance, diagnostic scale-up, or demographic risk profiles. For example, if TB case detection improved substantially in a country during periods of better system performance, reported TB incidence could rise even as true TB burden is falling—producing counterintuitive correlations. Similarly, TB incidence is affected by comorbidities and risk factors (e.g., HIV burden, diabetes prevalence, smoking, indoor air pollution, crowding) that are not explicitly modeled here, and these omitted time-varying factors can differ sharply across countries. The regression strategy mitigates some of this via fixed effects and controls, but it cannot fully eliminate time-varying confounding.

Limitations that should be stated explicitly

Several limitations should be acknowledged as they shape the strength of inference:

- Associational design: Even with controls and two-way fixed effects, the analysis remains observational and cannot guarantee causal interpretation.
- Small number of countries (clusters): With only 11 countries, cluster-robust inference can be unstable. The HC1 robustness check partially addresses this, but the limitation remains relevant.
- Proxy interpretation of ImmunizationIndex: The index may capture overall primary-care strength and governance quality, not only vaccine coverage in isolation.
- Omitted time-varying determinants: Lack of complete series for certain epidemiological and structural indicators (e.g., HIV incidence in the same country set) constrains the model's ability to isolate pathways.

Despite these limitations, the model sequence builds a consistent empirical narrative: immunization performance is descriptively correlated with lower TB incidence; the relationship becomes empirically clearer when TB is modeled proportionally and when immunization is allowed to operate with a lag; and infrastructure/connectivity indicators remain strongly associated with TB incidence reductions over time within countries.

5. Conclusions and Recommendations

5.1 Conclusions

Based on a balanced panel of 11 countries over 2000–2022 (N=253), the study reaches five defensible conclusions:

1. Descriptive evidence indicates a moderate negative immunization–TB association. The pooled correlation between immunization performance and TB incidence is $r = -0.504$ (Table 2), but the direction and magnitude vary substantially across countries (Table 3).
2. Immunization is not a robust predictor of TB incidence in level specifications once controls and fixed effects are applied. In pooled and fixed-effects levels models, the immunization coefficient remains negative

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but statistically non-significant (Table 4, M1–M2).

3. Modeling TB incidence proportionally improves detectability of the immunization association. In the two-way fixed effects log outcome model, immunization becomes marginally significant (M3: $\beta = -0.0034$, $p < .10$), suggesting a small within-country association when TB is analyzed in logarithmic form.

4. The strongest evidence supports a delayed association. In the lagged log fixed-effects model, last year's immunization performance predicts lower TB incidence (M4: ImmunizationIndex_L1 $\beta = -0.0054$, $p < .01$), implying that a 10-point improvement in immunization coverage is associated with roughly a 5.26% reduction in TB incidence in the following year.

5. Infrastructure and connectivity are consistently associated with lower TB incidence. Electricity access and internet use exhibit stable negative coefficients in the log fixed-effects models (Table 4, M3–M4), indicating that TB burden reductions co-move with broader development and system-capacity conditions.

5.2 Recommendations

The recommendations below are framed as evidence-informed and proportionate to the study's associational design.

1. Treat immunization performance as a health system capacity indicator—then strengthen it deliberately.

Since immunization improvements predict subsequent TB reductions in the lagged model (M4), countries should prioritize reliable vaccine supply chains, outreach systems, monitoring, and local-level delivery capacity. The emphasis should be on institutional strengthening rather than isolated campaigns.

2. Integrate immunization strengthening with TB control programs at the primary-care level.

Programmatic integration is recommended: shared community health worker platforms, synchronized outreach schedules, and unified local health information systems can amplify downstream benefits. The lag evidence supports planning cycles that view immunization improvement as contributing to broader communicable disease control in subsequent periods.

3. Prioritize infrastructure pathways as part of public health strategy.

Given the strong and consistent association of electricity access and internet use with reduced TB incidence in fixed-effects log models, public health planning should align with infrastructure development—particularly in underserved areas—because TB control depends on service reach, continuity of care, and information access.

4. Use the lag structure for operational evaluation and target setting.

Health agencies should design monitoring frameworks that explicitly track whether improvements in immunization coverage in year t are followed by improvements in TB-related indicators in year t+1 and beyond. This provides an operationally measurable logic consistent with the study's strongest specification.

5. Avoid overgeneralization across countries; pursue country-specific diagnostics.

Because the country-level correlations vary (Table 3), national agencies should conduct within-country diagnostics: identify whether immunization tracks system improvements, surveillance changes, or other reforms. Viet Nam's positive correlation, for example, suggests that the local relationship may be driven by country-specific dynamics that require separate interpretation.

5.3 Implications of Research Findings

Policy and program implications

The results imply that TB incidence reductions in ASEAN and China are linked to an ecosystem of improvements rather than a single determinant. Immunization performance appears to matter most when interpreted as a component of system strengthening and when evaluated with temporal delay. Public health policy should therefore emphasize multi-sector coordination (health delivery + infrastructure + digital reach) and should evaluate interventions using time-aware metrics rather than expecting immediate contemporaneous reductions.

Methodological implications

The progression from levels to log models and then to lagged specifications demonstrates that empirical conclusions are sensitive to functional form and timing. For communicable disease burden indicators that vary widely across countries, proportional modeling (log outcomes) may be more informative and stable. Introducing lags is not merely a statistical device but a conceptual alignment with plausible policy transmission mechanisms.

Theoretical implications

Conceptually, the study supports a "system-capacity" interpretation: immunization coverage—especially when combined into an index—may proxy governance quality, primary-care reach, and administrative reliability. In such a view, immunization does not merely prevent vaccine-targeted diseases; it signals broader capacity that also contributes to the control of other infectious diseases, including TB, through indirect channels.

Research implications and future directions

Future work should expand the covariate set where feasible (e.g., risk-factor indicators and programmatic variables), test alternative lag lengths, and explore heterogeneity explicitly (e.g., stratifying by baseline TB burden or income group). With additional countries or subnational panels, inference could be strengthened via dynamic panel methods and more robust cluster-based estimators. This would help distinguish whether immunization performance is a proxy for general system capacity or has an independent association beyond correlated development reforms.

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7. Tables

Table 1. Descriptive statistics (pooled, 2000–2022; N = 253)

Variable	Unit	Mean	SD	Min	Max
ImmunizationIndex	percent points	87.62	12.37	40.50	99.00
TB_incidence	per 100,000	254.28	182.92	39.00	853.00
GDP_pc	current US$	9,938.23	16,115.22	141.53	90,299.07
Sanitation_basic	percent points	75.45	20.20	10.45	100.00
Electricity_access	percent points	85.99	21.58	9.50	100.00
Internet_use	percent points	35.32	29.63	0.0003	98.97
HealthExp_GDP	% of GDP	3.70	1.14	1.82	6.92
OOP_share	percent points	41.64	18.66	4.86	85.90
ln_TB	natural log	5.25	0.80	3.66	6.75
ln_GDPpc	natural log	8.16	1.45	4.95	11.41

Table 2. Pearson correlations among main variables (pooled; N = 253)

	ImmunizationIndex	TB_incidence	GDP_pc	Sanitation_basic	Electricity_access	Internet_use	HealthExp_GDP	OOP_share
ImmunizationIndex	1.000	-0.504	0.384	0.658	0.558	0.445	-0.019	-0.409
TB_incidence	-0.504	1.000	-0.525	-0.669	-0.721	-0.600	0.207	0.602
GDP_pc	0.384	-0.525	1.000	0.510	0.361	0.619	-0.144	-0.430
Sanitation_basic	0.658	-0.669	0.510	1.000	0.777	0.758	-0.242	-0.505
Electricity_access	0.558	-0.721	0.361	0.777	1.000	0.604	-0.274	-0.601
Internet_use	0.445	-0.600	0.619	0.758	0.604	1.000	0.066	-0.509
HealthExp_GDP	-0.019	0.207	-0.144	-0.242	-0.274	0.066	1.000	0.205
OOP_share	-0.409	0.602	-0.430	-0.505	-0.601	-0.509	0.205	1.000

Table 3. Country-level correlation: ImmunizationIndex vs TB incidence (2000–2022)

Country	r
China	-0.891
Cambodia	-0.801
Lao PDR	-0.753
Philippines	-0.652
Indonesia	-0.461
Malaysia	-0.158
Singapore	-0.106
Thailand	-0.100
Myanmar	-0.024
Brunei Darussalam	0.042
Viet Nam	0.199

Table 4. Panel regression estimates of TB incidence on immunization performance and controls, 2000–2022

	M1	M2	M3	M4
ImmunizationIndex	-0.6434	-0.8317	-0.0034*	
	(3.3552)	(1.1252)	(0.0020)	
ImmunizationIndex_L1				-0.0054***
				(0.0012)
GDP_pc	-0.0024***	0.0002		
	(0.0007)	(0.0006)		
ln_GDPpc			-0.0686	-0.0814**
			(0.0749)	(0.0368)
Sanitation_basic	-0.6803	-0.8296	0.0003	0.0006
	(1.4996)	(1.3662)	(0.0049)	(0.0018)
Electricity_access	-3.6228**	-3.8940***	-0.0056**	-0.0055***
	(1.8393)	(0.9762)	(0.0024)	(0.0010)
Internet_use	-0.3025	0.4379	-0.0068***	-0.0061***
	(0.7324)	(1.0542)	(0.0026)	(0.0011)
HealthExp_GDP	1.3239	-5.1836	0.0396	0.0265
	(20.1663)	(14.1429)	(0.0439)	(0.0171)
OOP_share	1.6888	0.3632	0.0018	0.0012
	(1.2613)	(0.7734)	(0.0016)	(0.0010)
R-squared	0.6250	0.9631	0.9853	0.9886
R-squared Adj.	0.6143	0.9564	0.9826	0.9864
Country FE	No	Yes	Yes	Yes
SE type	cluster	cluster	cluster	HC1
Year FE	No	Yes	Yes	Yes

Standard errors in parentheses.
* p<.1, ** p<.05, ***p<.01

Dependent variable: TB incidence per 100,000 (Models 1–2, level); ln(TB incidence) (Models 3–4, log).

Notes: Standard errors in parentheses. M1–M3 use country-clustered SE; M4 uses HC1 robust SE. Country and year fixed-effect coefficients are omitted for brevity.

Significance: * p<0.10, ** p<0.05, *** p<0.01.