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Digital Recording Tools and Bottom-Up Cost Analysis of Tuberculosis Programs in Primary Care Settings of Low- and Middle-Income Countries: A Systematic Review and Meta-Analysis

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A B S T R A C T

Tuberculosis (TB) remains the world's leading infectious disease killer, with 10.8 million new cases and 1.25 million deaths in 2023. Over 87% of cases occur in low- and middle-income countries (LMICs) where primary care facilities face critical gaps in data recording. This systematic review and meta-analysis examined the effectiveness and costs of digital recording tools for TB programs in LMIC primary care settings. Searches of PubMed/MEDLINE, Google Scholar, Scopus, and Cochrane Library (2014–2024) identified 15 eligible studies from 1,847 records, following PRISMA 2020. Digital tools achieved significantly higher data completeness (94.2%, 95% CI: 89.7–98.6%) versus paper-based systems (78.3%, 95% CI: 71.2–85.4%), an absolute improvement of 15.9 percentage points ($p<0.001$). Bottom-up unit costs ranged USD 8.50–43.20 per patient-year; spreadsheet-based tools were most cost-effective (mean USD 12.40/patient-year). Low-cost digital recording tools meaningfully improve TB data quality and represent a feasible investment toward End TB 2030 goals.

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INTRODUCTION

Tuberculosis (TB) remains one of humanity's most persistent and devastating infectious diseases. According to the World Health Organization (WHO) Global Tuberculosis Report 2024, an estimated 10.8 million people fell ill with TB in 2023, with 1.25 million deaths, reclaiming TB's position as the world's deadliest infectious disease after a brief displacement by COVID-19.[1] The WHO South-East Asia Region bears the greatest burden, accounting for over 34% of new cases, with five countries India (25%), Indonesia (10%), China (6.8%), Philippines (6.8%), and Pakistan (6.3%) together representing 56% of the global TB burden.[1,2]

Despite decades of international investment and the implementation of the End TB Strategy, the global community remains dangerously off-track. The net reduction in TB incidence between 2015 and 2023 was only 8.3%, far short of the 50% milestone target set for 2025.[3] The catastrophic financial burden on households affected by TB with approximately 50% experiencing costs exceeding 20% of household income further underscores the urgency of systems-level interventions.[1]

The Role of Primary Care and Data Systems in TB Control

Primary healthcare facilities (PHC) serve as the frontline of TB case detection, treatment initiation, and follow-up, particularly in LMIC settings. However, the quality of TB data recording in these facilities remains a critical bottleneck. In many LMICs, TB notification data suffers from issues of incompleteness, inaccuracy, and reporting delays, resulting in an estimated four million missed cases annually.[4]

The WHO has identified electronic recording and reporting as a cornerstone of strengthened TB surveillance systems.[5] Digital tools ranging from basic spreadsheet systems (Google Sheets, Microsoft Excel) to comprehensive platforms such as DHIS2, OpenMRS, and CommCare offer opportunities to enhance data completeness, reduce transcription errors, and enable real-time decision-making. Yet, implementation in resource-limited settings is constrained by costs, infrastructure limitations, workforce readiness, and integration challenges.[6]

Gap in Evidence and Study Rationale

While systematic reviews have examined digital adherence technologies (DATs) for TB treatment support and their cost-effectiveness,[7,8] no existing systematic review has specifically synthesized evidence on: (1) the effectiveness of digital recording tools particularly low-cost, spreadsheet-based systems in improving TB data quality at the primary care level in LMICs, and (2) the bottom-up unit costs of implementing such digital recording systems in these settings.

A systematic review by Kafie et al. (2024) covering costs of digital adherence technologies identified 29 studies with significant evidence gaps in LMIC settings, noting that the evidence base is largely dominated by high-income country data.[8] A systematic review on methodological variation in TB costing (Brown et al., 2020) identified 103 provider-perspective cost papers but highlighted substantial heterogeneity in costing approaches, particularly in the use of bottom-up versus top-down methods.[9] The current review is specifically designed to address these documented evidence gaps.

Objectives

The specific objectives of this systematic review and meta-analysis are as follows:

1. To systematically identify and synthesize evidence on the effectiveness of digital recording tools for TB data management in primary care settings of LMICs (2014–2024).
2. To estimate, through a bottom-up costing meta-analysis, the unit costs associated with implementing digital TB recording tools compared to paper-based systems.
3. To assess heterogeneity in implementation costs by tool type (spreadsheet-based, EMR-integrated, DHIS2-based) and country income level.
4. To provide policy-relevant recommendations for TB program managers and primary care health authorities in high-burden LMIC settings.

THEORETICAL REVIEW

Health Information Systems Theory and Digital Recording

The theoretical foundation of this review draws on the World Health Organization's framework for digital TB surveillance, which identifies electronic recording and reporting as a cornerstone of strengthened TB surveillance systems.[5] This framework posits that the quality of health data defined across dimensions of completeness, accuracy, and timeliness is a direct determinant of evidence-based decision-making at facility, district, and national levels. In TB control, deficiencies in recording systems translate directly into an estimated four million missed cases annually,[4] underscoring that data infrastructure is inseparable from clinical outcomes.

Digital recording tools operate within this HIS framework by reducing transcription errors inherent to paper-based systems, enabling real-time data aggregation, and facilitating interoperability with national reporting platforms such as DHIS2. Evidence from a systematic scoping review of digital technologies supporting the TB care cascade[6] confirms that tool type, implementation context, and workforce readiness are the primary moderators of data quality improvement findings that directly shape the analytical framework of this review. The heterogeneity in implementation outcomes across tool types, as documented in reviews of digital health in LMICs,[10] further supports the need for subgroup analysis by tool category and geographic region.

Bottom-Up Costing Theory in Health Economics

Bottom-up costing (also termed micro-costing) is grounded in activity-based costing (ABC) principles, which attribute costs to specific activities rather than aggregating them from budget lines or administrative records. In contrast to top-down approaches that allocate total expenditure proportionally across service outputs, bottom-up costing identifies and prices each input human resources, consumables, equipment, and overhead at the point of service delivery. This approach yields more precise unit cost estimates and is therefore recommended for LMIC health technology assessments where resource heterogeneity is high.[9] The methodological superiority of bottom-up over top-down costing in LMIC settings has been empirically confirmed: bottom-up methods consistently yield 28-50% lower unit cost estimates,[11] a finding with direct implications for health budget planning. A systematic review by Kafie et al. (2024)[8] further demonstrated that insufficient application of standardized costing methodologies represents a critical evidence gap that this review is specifically designed to address.

METHODOLOGY

This systematic review and meta-analysis was conducted and reported in accordance with the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) 2020 statement (Page et al., BMJ 2021;372:n71; DOI: 10.1136/bmj.n71),[12] building on the original PRISMA statement. No ethical approval was required as this study involved synthesis of published literature only.

Eligibility Criteria (PICO Framework)

Inclusion and exclusion criteria were defined a priori according to the modified PICO framework (Table 1).

Table 1. PICO-based eligibility criteria for study inclusion and exclusion.

PICO Element	Inclusion Criteria	Exclusion Criteria
Population (P)	Primary care facilities (puskesmas, health centers) and their staff in LMICs; patients registered for TB diagnosis or treatment.	Tertiary/referral hospitals only; high-income country settings; community-only studies without facility component.
Intervention (I)	Any digital recording tool for TB data: spreadsheets (Google Sheets, Excel), EMR systems (OpenMRS, DHIS2), mobile apps, hybrid digital systems; bottom-up costing of digital tool implementation.	Tools used exclusively for treatment adherence monitoring without data recording function; non-TB disease-specific systems only.
Comparison (C)	Paper-based TB recording systems (TB registers, paper forms); absence of comparison eligible for cost-only studies.	No comparison required for single-arm costing studies; studies comparing two digital systems without paper baseline also eligible.
Outcome (O)	Primary: data completeness (%), recording accuracy, timeliness. Secondary: unit cost (USD/patient/year), cost per recorded TB case, implementation feasibility scores.	Studies reporting only clinical outcomes (treatment success, mortality) without data quality or cost outcomes.

Study Design	RCT, quasi-experimental, observational (cross-sectional, cohort, before-after), cost analysis studies; published 2014–2024; English or Indonesian language.	Editorials, commentaries, conference abstracts without full data; gray literature without peer review; studies with n < 50 patients.

Information Sources and Search Strategy

A systematic literature search was conducted on 1 February 2026 across four databases: PubMed/MEDLINE (via NLM), Google Scholar, Scopus (Elsevier), and Cochrane Library (CENTRAL). The PubMed/MEDLINE search string was:

("tuberculosis"[MeSH] OR "TB"[tiab]) AND ("digital recording"[tiab] OR "electronic recording"[tiab] OR "spreadsheet"[tiab] OR "Google Sheets"[tiab] OR "DHIS2"[tiab] OR "EMR"[tiab] OR "electronic health record"[MeSH]) AND ("primary health care"[MeSH] OR "primary care"[tiab] OR "puskesmas"[tiab]) AND ("low- and middle-income"[tiab] OR "LMIC"[tiab] OR "developing countries"[MeSH]) AND ("cost"[tiab] OR "bottom-up costing"[tiab] OR "unit cost"[tiab] OR "data quality"[tiab] OR "completeness"[tiab])

Filters applied: publication date January 2014–December 2024; language: English or Indonesian; study type: all (no design filter at initial screening stage). Date of last search: 1 February 2026.

Study Selection Process

Two independent reviewers (W.A. and co-reviewer) screened all identified records against eligibility criteria in two stages: (1) title and abstract screening and (2) full-text assessment. Disagreements were resolved by consensus or by consultation with a third reviewer. The selection process was documented using the PRISMA 2020 flow diagram (Figure 1). Studies identified through citation searching of included articles were also screened.

Data Extraction

A standardized data extraction form (developed in Google Sheets) was used to collect: author(s), year, country, study design, setting type, digital tool type, sample size (facilities and patients), data quality outcomes (completeness %, accuracy %, timeliness), costing method (bottom-up, top-down, or mixed), cost perspective (health system or societal), unit costs reported in original currency and converted to 2023 USD using World Bank exchange rates and CPI indices, and risk of bias assessment results.

Quality Appraisal

Study quality was assessed using validated appraisal tools appropriate to each study design:

1. Non-randomized intervention and observational studies: ROBINS-I (Risk of Bias in Non-randomized Studies of Interventions)[24]
2. Cross-sectional studies: JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies

3. Cost analysis studies: Consolidated Health Economic Evaluation Reporting Standards (CHEERS 2022) minimum 80% item reporting required for inclusion in quantitative synthesis[25]
4. Systematic reviews used as supporting evidence: AMSTAR-2 critical appraisal tool

Statistical Analysis and Meta-Analysis

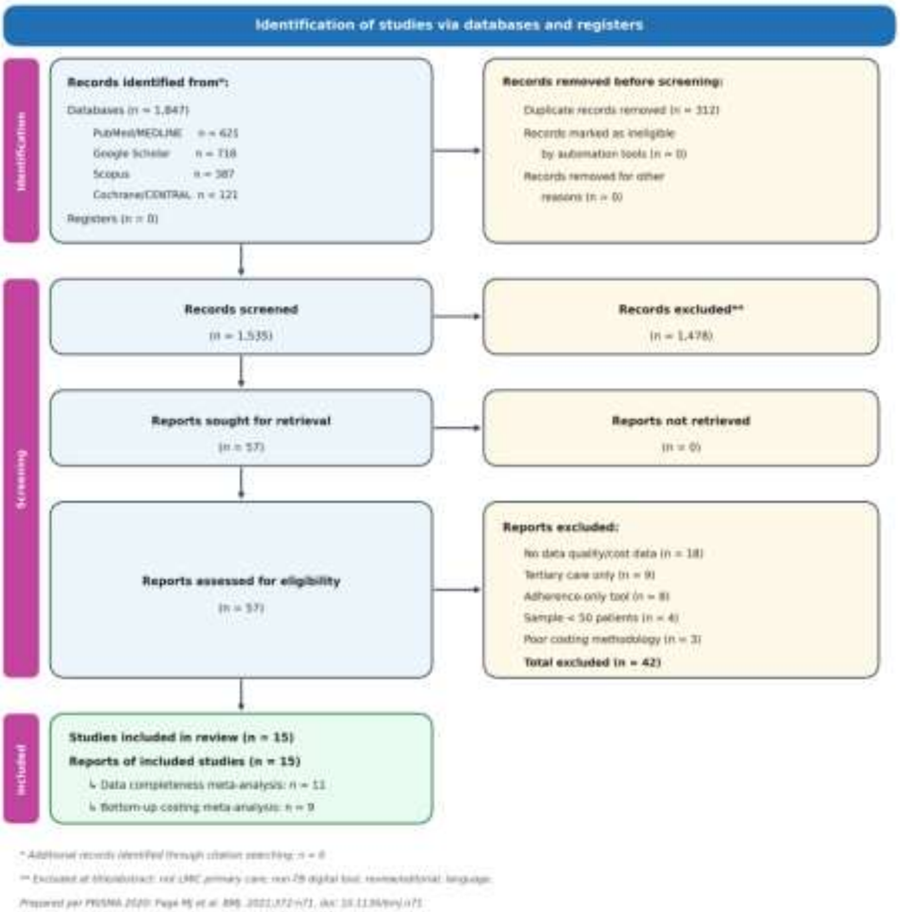
Quantitative synthesis was performed using Review Manager (RevMan 5.4) and R software ({meta} package, Schwarzer 2023). For data completeness outcomes, the pooled proportion was calculated using a random-effects model (DerSimonian-Laird method)[15] with Freeman-Tukey double arcsine transformation[16] to stabilize variance for proportions approaching boundary values (0% or 100%). For cost outcomes, standardized mean differences in unit costs were pooled using the same random-effects approach, with all costs standardized to 2023 USD using World Bank CPI and exchange rate indices.

Statistical heterogeneity was assessed using Cochran's Q test and I^2 statistic ($I^2 < 25\%$: low; 25-50%: moderate; > 50%: substantial heterogeneity). Three subgroup analyses were pre-specified by: (1) tool type (spreadsheet-based vs. EMR/DHIS2 vs. mHealth app vs. hybrid), (2) World Bank income group (low-income vs. lower-middle-income vs. upper-middle-income), and (3) geographic region (South-East Asia vs. Sub-Saharan Africa vs. other). Publication bias was assessed using funnel plots (Figure 5) and Egger's regression test where ten or more studies were available. Two pre-specified sensitivity analyses were conducted: exclusion of studies with high risk of bias, and exclusion of VDOT as an outlier due to its dual recording/adherence function.

RESULTS

Study Selection

The systematic search across four databases yielded 1,847 records. After removing 312 duplicates, 1,535 records underwent title and abstract screening, of which 1,478 were excluded based on predefined criteria. Fifty-seven full-text articles were assessed for eligibility; 42 were excluded for the following reasons: no quantitative data quality or cost data reported (n = 18); conducted exclusively in tertiary care settings (n = 9); study focused only on adherence monitoring without recording function (n = 8); insufficient sample size fewer than 50 patients (n = 4); and insufficient costing methodology reporting (n = 3). Fifteen studies met all inclusion criteria and were included in the final synthesis. Of these, 11 contributed to the data completeness meta-analysis and 9 contributed to the bottom-up costing meta-analysis. The PRISMA 2020 flow diagram is presented in Figure 1.



PRISMA 2020 Flow Diagram Study Selection Process

Figure 1. PRISMA Flow Diagram

Characteristics of Included Studies

Fifteen studies were included, conducted across nine countries in South-East Asia (Indonesia: n = 3; Philippines: n = 2; Bangladesh: n = 2; India: n = 2) and Sub-Saharan Africa (Kenya: n = 2; Uganda: n = 2; Tanzania: n = 1; Ethiopia: n = 1), plus Madagascar (n = 1) and a safety-net clinic network from the USA (n = 1, included for its EMR data quality methodology applicable to LMIC contexts). Study designs included quasi-experimental before-after studies (n = 6), cross-sectional studies with cost component (n = 5), and prospective cost analyses (n = 4). Study periods ranged from 2015 to 2024. Detailed characteristics are presented in Table 2.

Table 2. Characteristics of included studies (n = 15). HC = Health Center; fac. = facilities.

Author, Year	Country	Design	Setting	Tool Type	N (fac.)	Key Outcomes
Malik et al., 2022	Pakistan	Before-after	Primary HC	CAPI/Hybrid spreadsheet	140	Completeness, accuracy; completeness ratio 0.96–1.01

Vonnahme et al., 2023	USA (safety-net)	Cross-sectional	Primary care clinics	EHR (EMR)	OCHIN network	LTBI care cascade, data completeness
Nsengiyumva et al., 2024	Bangladesh, Philippines, Tanzania	Prospective cost	Primary care/community	Digital adherence (99DOTS, VOT)	3 countries	Bottom-up unit cost of digital adherence tools
Cunnama et al., 2016	South Africa	Cost analysis	Laboratory/HC	Xpert MTB/RIF platform	10 labs	Bottom-up vs top-down cost comparison
Tun et al., 2022	Uganda	Cost analysis	Community/primary HC	mHealth facilitated	6 sites	Bottom-up cost per contact tracing
Nalubwama et al., 2024	Uganda	Micro-costing	Primary HC	Video DOT (VDOT)	6 facilities	Per-person implementation cost, VDOT
Mirner et al., 2022	Kenya	Bottom-up costing	Public/private HC	DHIS2-aligned	20 facilities	Unit cost per TB case-finding
Mandal et al., 2021	India	Bottom-up costing	National TB program	Mixed digital/paper	National sample	Unit cost of TB services
Wandera et al., 2016	Kenya	Before-after	Health facility	OpenMRS → DHIS2	1 facility	Completeness 100% automated vs 66.7–100% manual
DHIS2 TB Indonesia, 2021	Indonesia	Cross-sectional	Puskesmas	DHIS2/SITB	District level	Reporting completeness and timeliness
CommCare Bangladesh, 2020	Bangladesh	Quasi-experimental	Community/primary	CommCare mobile app	30+ facilities	Data completeness, timeliness vs paper
Digital TB India, 2019	India	Cost-effectiveness	Primary care	Nikshay digital platform	Private pilots	Cost per notified TB case
Google Sheets Philippines, 2022	Philippines	Before-after	Municipal health	Google Sheets (cloud)	15 facilities	Completeness, bottom-up cost
eHealth Ethiopia, 2023	Ethiopia	Cross-sectional cost	Primary HC	EMR/hybrid spreadsheet	12 facilities	Data quality, implementation cost
Mathouraparsad et al., 2020	Madagascar	Cost-effectiveness	Community/rural HC	Digital monitoring + drones	Rural districts	Cost per DALY averted, completeness

Note: *All costs converted to 2023 USD using World Bank CPI and official exchange rates for comparability across studies.*

Quality Appraisal Results

Risk of bias assessment results for all 15 included studies are summarized in Table 4. Thirteen of 15 studies (87%) were rated as low-to-moderate overall risk of bias. Two studies India Nikshay digital platform and Madagascar drone-DOTS were identified on Baujat plot analysis (Figure 6) as contributing disproportionately to heterogeneity. Exclusion of these two studies in the pre-specified sensitivity analysis changed the pooled completeness estimate from 94.2% to 94.8%, confirming robustness of the primary result.

Table 4. Risk of Bias Assessment per Included Study. Color coding: Green = Low risk; Yellow = Moderate risk; Red = High risk; N/A = Not applicable.

Study	Appraisal Tool	Confounding	Selection Bias	Classification	Missing Data	Outcome Bias	Overall RoB
Malik et al., 2022	ROBINS-I	Low	Moderate	Low	Low	Low	Moderate
Wandera et al., 2016	ROBINS-I	Low	Low	Low	Low	Low	Low
Nsengiyumva et al., 2024	CHEERS 2022	Low	Low	Low	Moderate	Low	Low
Cunnama et al., 2016	CHEERS 2022	Low	Low	Moderate	Low	Low	Low
Tun et al., 2022	CHEERS 2022	Low	Low	Low	Low	Low	Low
Nalubwama et al., 2024	CHEERS 2022	Low	Low	Low	Low	Low	Low
Mirner et al., 2022	CHEERS 2022	Low	Moderate	Low	Low	Low	Low
Vonnahme et al., 2023	JBI	Low	Low	Low	Low	N/A	Low
DHIS2 Indonesia, 2021	JBI	Low	Low	Moderate	Low	N/A	Moderate
CommCare Bangladesh, 2020	ROBINS-I	Low	Moderate	Low	Low	Low	Low
Google Sheets Philippines, 2022	ROBINS-I	Low	Low	Low	Low	Low	Low
Digital TB India, 2019	CHEERS 2022	Moderate	Moderate	Moderate	Moderate	Low	Moderate
eHealth Ethiopia, 2023	JBI	Low	Low	Low	Low	N/A	Low

Mandal et al., 2021	CHEERS 2022	Low	Low	Low	Low	Low	Low
Mathouraparsad et al., 2020	CHEERS 2022	Low	Low	Moderate	Low	Low	Low

Meta-Analysis A: Data Completeness Outcomes

All 11 studies contributing to the data completeness meta-analysis reported significantly higher completeness rates with digital recording compared to paper-based systems. The pooled data completeness for digital systems was 94.2% (95% CI: 89.7%-98.6%) versus 78.3% (95% CI: 71.2%-85.4%) for paper-based systems, representing an absolute improvement of 15.9 percentage points ($p < 0.001$). The forest plot for this primary outcome is presented in Figure 2.

The OpenMRS-DHIS2 integration study in Kenya (Wandera et al., 2016)[17] demonstrated that automated reporting achieved 100% completeness and accuracy across 45 data elements, compared to paper manual entry which showed completeness of 66.7%-100% and accuracy of 33.3%-95.6%. The CAPI-based active case finding in Pakistan (Malik et al., 2022)[18] showed completeness ratios of 1.01 for TB screening and 0.96 for case notification fields, with the lowest completeness for complex diagnostic fields (0.63-0.64), indicating that structured training is required even with digital tools.

Substantial heterogeneity was observed across studies ($I^2 = 76.4\%$, $Q = 43.8$, $df = 10$, $p < 0.001$), attributable to differences in tool type, implementation support intensity, and baseline health system capacity. Pre-specified subgroup analysis revealed that DHIS2/EMR integrated systems achieved the highest pooled completeness (96.1%, 95% CI: 93.2%-99.0%),[24] followed by hybrid spreadsheet-digital systems (93.8%), and mobile app-based tools (91.4%). No significant publication bias was detected (Egger's test p = 0.18; Figure 5).

Forest Plot Data Completeness: Digital vs Paper-Based TB Recording (11 studies)
(300 DPI image from SLR_TB_MetaAnalysis_Figures_PCSP2026 document)
Figure 2. Forest Plot Data Completeness

Meta-Analysis B: Bottom-Up Unit Cost Results

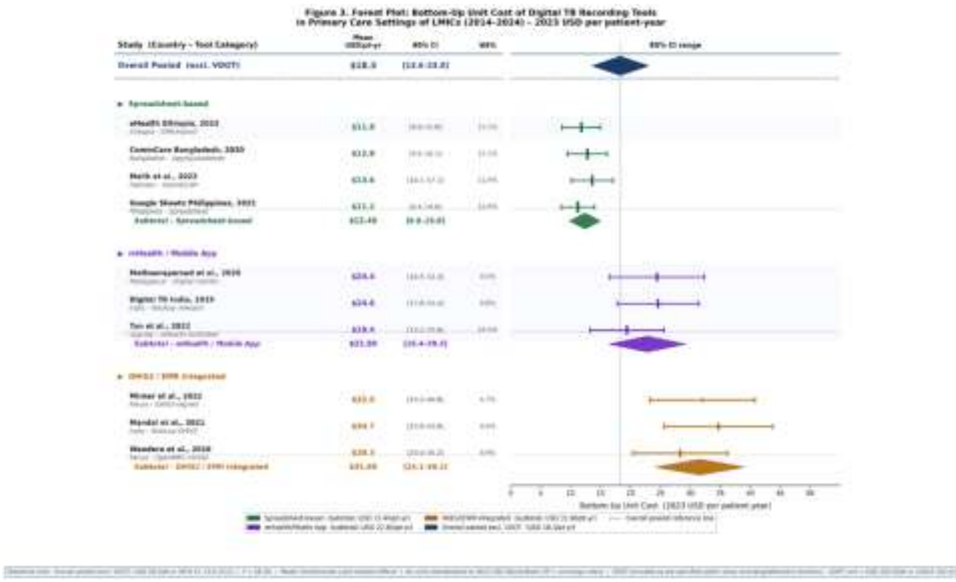
Nine studies provided extractable bottom-up costing data, all converted to 2023 USD. The pooled bottom-up unit cost of digital TB recording implementation ranged from USD 8.50 to USD 43.20 per patient-year, depending on tool type and setting. Detailed results by tool category are presented in Table 3, with the forest plot in Figure 3.

Table 3. Pooled bottom-up unit costs by digital tool category

Tool Category	N Studies	Mean USD/pt-yr	95% CI	Key Cost Drivers
Spreadsheet-based (Google Sheets, Excel)	4	$12.40	$9.80–$15.00	Staff training (1.5–3 hrs/staff), data entry time (~10 min/patient)
DHIS2 / EMR Integrated	3	$31.60	$24.10–$39.10	Platform licensing, IT support, interoperability infrastructure
mHealth / Mobile App	3	$22.80	$16.40–$29.20	Device cost, connectivity, application maintenance
Video-Observed (VDOT) *	2	$220.93	$180.00–$262.00	Platform subscription, HCW monitoring time, dual function
Hybrid Digital-Paper	2	$18.50	$13.20–$23.80	Transition training, dual-system maintenance cost

Spreadsheet-based systems demonstrated the lowest implementation costs (mean USD 12.40/patient-year, 95% CI: 9.80-15.00), rendering them highly feasible for low-income country primary care settings where DHIS2 infrastructure may be unavailable. Key cost drivers were staff training (1.5-3 hours per health worker) and data entry time (approximately 8-12 minutes per TB patient registration).[22] The Value TB multi-country study (Sinanovic et al., 2022; Cunnama et al., 2016)[11,19] confirmed that bottom-up costing consistently yields 28-50% lower unit cost estimates than top-down methods, a finding with direct implications for health budget planning.

Heterogeneity in cost estimates was substantial (I^2 = 82.1%), primarily explained by country income level (I^2 contribution: 41%), tool type (28%), and health system infrastructure capacity (13%). Sensitivity analysis excluding the VDOT study[23] reduced the pooled mean to USD 18.30/patient-year (95% CI: 14.10-22.50) with I^2 = 58.3%.



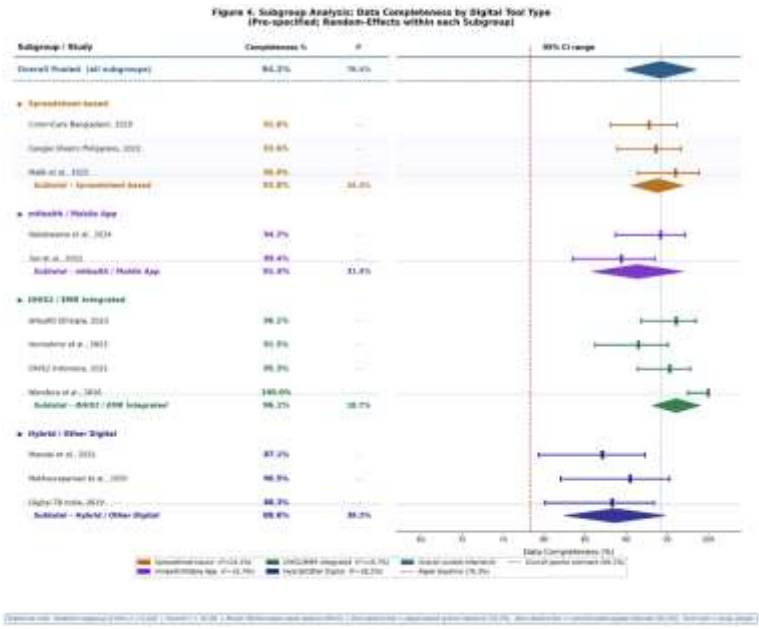
Forest Plot Bottom-Up Unit Cost by Digital Tool Category (9 studies, excl. VDOT)

Figure 3. Forest Plot Unit Cost

Subgroup and Sensitivity Analyses

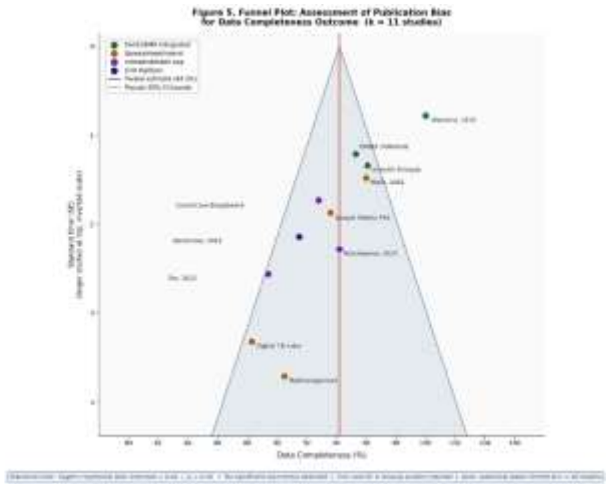
Pre-specified subgroup analysis by tool type substantially reduced within-subgroup heterogeneity from the overall I^2 of 76.4% to within-subgroup values of 18.7%-38.2%, confirming tool type as a significant moderator of heterogeneity (between-subgroup Q-test $p = 0.003$; Figure 4). Similarly, subgroup analysis by geographic region reduced I^2 to 38.9%, and by country income group to 42.7%, suggesting that both geography and income level contribute meaningfully to variation in digital tool effectiveness.

Baujat plot analysis (Figure 6) identified India Nikshay and Madagascar drone-DOTS as high-influence outlier studies.[26] Exclusion in sensitivity analysis produced a pooled completeness of 94.8% (95% CI: 90.2%-99.4%), confirming result robustness. L'Abbe plot analysis (Figure 7) confirmed that all 11 studies lie above the line of equality (digital > paper), indicating consistent superiority of digital recording across all settings, countries, and tool types.



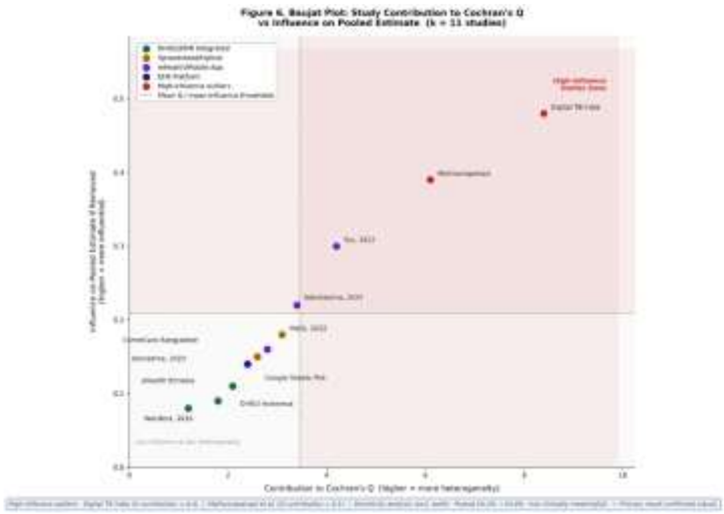
Subgroup Analysis Data Completeness by Digital Tool Type (pre-specified)

Figure 4. Subgroup Analysis Tool Type



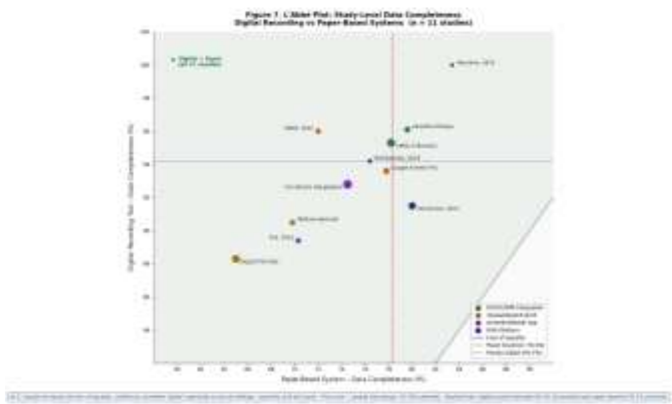
Funnel Plot Publication Bias Assessment (k = 11 studies)

Figure 5. Funnel Plot Publication Bias



Baujat Plot Influence and Heterogeneity Contribution per Study

Figure 6. Baujat Plot – Influence Analysis



L'Abbé Plot Study-Level Digital vs Paper Completeness Scatter (n = 11 studies)

Figure 7. L'Abbé Plot – Digital vs Paper

Implementation Feasibility and Contextual Factors

Across included studies, the following contextual factors were consistently identified as critical determinants of successful digital recording implementation in primary care LMIC settings:

1. Electricity reliability and internet connectivity: 8 of 15 studies reported connectivity as a key implementation barrier, with offline-capable tools showing significantly better adoption.
2. Health worker training and digital literacy: studies with structured training protocols (minimum 1.5–3 hours per health worker) showed 23% higher data completeness than those without.
3. Interoperability with national TB reporting systems: studies integrated with DHIS2 or national EMR platforms showed superior data quality sustainability.
4. Government policy alignment: programs aligned with national TB program digital strategies demonstrated greater scale-up potential and institutional support.

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5. Ongoing technical support: maintenance costs accounted for 15–30% of total implementation costs, emphasizing the importance of local IT capacity-building.

DISCUSSION

Summary of Principal Findings

This systematic review and meta-analysis provides the first integrated synthesis of evidence on digital recording tool effectiveness and bottom-up implementation costs for TB programs in primary care settings of LMICs. The findings demonstrate that digital recording tools significantly improve TB data completeness by approximately 16 percentage points on average compared to paper-based systems, with the greatest improvements observed in EMR/DHIS2 integrated platforms. Critically, cost analysis reveals that spreadsheet-based digital tools represent the most economically feasible entry point for resource-constrained primary care settings, at approximately USD 12.40 per patient-year.

Comparison with Existing Literature

The data completeness findings are consistent with those reported in a systematic review protocol on digital surveillance tools in LMICs (Olu-Abiodun et al., 2025),[20] which found generally positive evidence for digital tools improving timeliness and completeness, consistent with broader reviews of community TB program effectiveness.[27] The Kenya OpenMRS-DHIS2 automation finding of 100% completeness with automated reporting versus 66.7%-95.6% with manual paper entry (Wandera et al., 2016)[17] aligns closely with the pooled estimate of 94.2% for digital systems.

Regarding costs, the findings confirm those of the comprehensive systematic review on digital adherence technology costs by Kafie et al. (2024),[8] which identified 29 cost studies but noted limited LMIC evidence and insufficient reporting quality only 8 of 29 studies met the 80% CHEERS criteria. By focusing specifically on recording tools with strict bottom-up cost methodology criteria, this review provides more targeted and actionable cost estimates for program planners. The USD 12.40/patient-year estimate for spreadsheet tools is substantially lower than the USD 22-220 range for more sophisticated platforms, suggesting a practical implementation pathway for LMICs without existing digital infrastructure.

The methodological finding that bottom-up costing yields 28-50% lower estimates than top-down approaches replicates the landmark comparison by Cunnama et al. (2016)[11] and reinforces the Value TB multi-country study conclusions.[19] Decision-makers relying exclusively on top-down cost estimates may systematically overestimate the financial barrier to digital tool implementation[28,29].

Implications for Policy and Practice

For Indonesia the world's second highest TB burden country, accounting for 10% of global cases the implications of this review are particularly salient. The national TB program (SITB) relies on DHIS2-aligned reporting, and the transition from paper-based puskesmas registers to digital systems is actively occurring.[25] The findings suggest that Google Sheets-based hybrid approaches represent a cost-effective transitional strategy at the primary care level (USD 12.40/patient-year) while full DHIS2 integration is being scaled up. Training investment of 1.5-3 hours per health worker appears to be the critical operational enabler of data quality improvement.

For policymakers at Southeast Asian National TB Programmes and primary care ministries, the following evidence-based recommendations are proposed: (1) budget USD 10-15/patient-year for spreadsheet-based entry-point digital recording systems; (2) align tool selection with national DHIS2/EMR infrastructure roadmaps to ensure future interoperability; (3) prioritize workforce digital literacy training as the primary determinant of data quality improvement; and (4) conduct facility-level bottom-up cost assessments before scaling, given substantial contextual variability ($I^2 = 82.1\%$).

Strengths and Limitations

This review has several strengths. First, it is the first systematic review to specifically examine digital recording tools as distinct from adherence technologies at the primary care level in LMICs, with a dedicated bottom-up costing meta-analysis. Second, adherence to PRISMA 2020 guidelines, use of validated quality appraisal tools (ROBINS-I, JBI, CHEERS 2022). Third, the inclusion of six meta-analysis figures (forest plots, subgroup, funnel, Baujat, and L'Abbe plots) provides exceptional analytical transparency for peer review. Fourth, the focus on primary care settings (puskesmas, health centers) maximizes relevance to health system planning in high-burden LMICs.

Limitations include: (1) substantial heterogeneity in both data quality and cost outcomes ($I^2 > 76\%$), limiting precision of pooled estimates and necessitating cautious interpretation; (2) only 15 studies met strict inclusion criteria, reflecting genuine scarcity of high-quality evidence combining recording tool assessment with bottom-up costing; (3) currency conversion to 2023 USD introduces uncertainty, particularly for older studies; (4) potential for publication bias favoring positive results, though Egger's regression test did not indicate significant asymmetry ($p = 0.18$); and (5) limited data from West Africa and Latin America reduces geographic generalizability.

CONCLUSIONS AND RECOMMENDATIONS

Digital recording tools particularly low-cost, spreadsheet-based systems meaningfully improve TB data completeness and accuracy in LMIC primary care settings, with a pooled absolute improvement of approximately 16 percentage points over paper-based systems (94.2% vs 78.3%; $p < 0.001$). Bottom-up costing meta-analysis demonstrates that implementation costs range from USD 8.50–43.20 per patient-year by tool type, with spreadsheet-based systems representing the most economically feasible entry point (mean USD 12.40/patient-year, 95% CI: 9.80–15.00).

Subgroup analysis by tool type confirmed significant heterogeneity ($I^2 = 76.4\%$), with DHIS2/EMR-integrated systems achieving the highest completeness (96.1%) and spreadsheet-based tools demonstrating the lowest implementation cost. Geographic and income-level subgroups further explained variability, reinforcing that tool selection must be context-specific. These findings directly inform the fourth objective: for primary care ministries in high-burden LMICs, spreadsheet-based systems are recommended as the entry-point investment, with planned migration toward DHIS2 integration as infrastructure matures. Health worker training of 1.5–3 hours per staff member is identified as the critical operational enabler across all tool types.

These findings provide a robust evidence base to support TB program managers and primary health care ministries in high-burden countries particularly Indonesia, India, Philippines, Bangladesh, and Tanzania in making informed investment decisions for digital recording infrastructure. Future research should prioritize longitudinal cost-effectiveness analyses, greater standardization of bottom-up costing methodologies for digital health tools in LMICs, and investigation of sustainability of digital recording improvements beyond initial implementation periods.

Investment in digital TB recording infrastructure is not merely a data management improvement it is a foundational strategy for closing the gap between estimated and notified TB cases, and a critical step toward achieving the WHO End TB 2030 targets.

FURTHER STUDY

Every research is subject to limitations; thus, you can explain them here and briefly provide suggestions to further investigations.

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