

Comparative Effectiveness of SMS, Phone Call, and Combined mHealth Interventions on Tuberculosis Knowledge: A Longitudinal Study from Lagos, Nigeria

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Abstract

Background

Tuberculosis (TB) remains a major public health challenge in Nigeria, where poor treatment adherence and inadequate patient knowledge continue to contribute to adverse treatment outcomes and multidrug-resistant TB. Patient knowledge is a key upstream determinant of treatment outcomes, yet scalable strategies for improving TB knowledge in low-resource settings remain limited. This study evaluated the comparative and combined effectiveness of SMS and phone-call mHealth interventions on TB knowledge among patients undergoing Directly Observed Treatment, Short-course (DOTS) therapy in Lagos State, Nigeria.

Methods

A quasi-experimental longitudinal study was conducted across 12 DOTS centres in four local government areas. A total of 128 adults with laboratory-confirmed TB were allocated to four arms: SMS only, phone-call only, combined SMS and phone-call, and standard care (control), with 32 participants per arm. TB knowledge was assessed at baseline, 6th week, and 12th week. Data were analysed using Generalized Estimating Equations (GEE) with a binomial distribution and logit link, adjusting for age category and education level. A secondary analysis examined the association between TB knowledge and medication adherence using Spearman rank correlations and a separate GEE model.

Results

Zero attrition was recorded. Phone-call interventions produced the largest knowledge gains (OR = 9.24, 95% CI: 4.07–20.99, $p < 0.001$), followed by SMS (OR = 3.67, 95% CI: 1.63–8.27, $p = 0.002$). The combined SMS-plus-phone-call intervention showed no significant benefit over standard care (OR = 0.61, 95% CI: 0.29–1.29, $p = 0.197$), with estimated marginal means below those of the control group. Significant knowledge gains emerged only at 12-week follow-up (OR = 2.38, $p = 0.001$), not at midline. The knowledge-adherence correlation attenuated from significant at baseline ($r_s = 0.326$, $p < 0.001$) and midline ($r_s = 0.267$, $p = 0.002$) to non-significant at follow-up ($r_s = 0.066$, $p = 0.457$).

Conclusion

Phone-call and SMS interventions significantly improved TB knowledge, with phone-calls demonstrating superior effectiveness. Contrary to expectations, combining both modalities conferred no benefit over standard care, suggesting that communication quality and channel appropriateness outweigh message volume. TB programmes should prioritize interactive voice-based follow-up and use SMS as a scalable alternative, while avoiding the uncritical combination of multiple communication channels.

Introduction

Tuberculosis (TB) persists as a major global health challenge, and worldwide progress in reducing its burden is falling well short of the targets set for 2030(1). TB incidence remains heavily concentrated in a few key nations, with 30 high-burden countries accounting for 87% of global cases in 2024; two-thirds (67%) of those cases were attributable to just eight countries. India alone accounts for a quarter of the world's cases, followed by Indonesia, the Philippines, China, Pakistan, Nigeria, the Democratic Republic of the Congo, and Bangladesh(1–3).

Most low- and middle- income countries (LMICs) still struggle with TB (4). Across all tiers of TB incidence globally, the African region bears a disproportionate share of global cases, deaths, and the associated socioeconomic consequences. In 2024, 11 countries reported incidence rates of 300–499 per 100,000, and another 20 reported rates of 100–299 per 100,000, spanning West, East, and Southern Africa.

Nigeria bears a substantial share of the global TB burden, ranking among countries with the highest estimated TB incidence in the world(5–7)The latest WHO Global Tuberculosis Report (2025) confirms Nigeria's contribution of 4.8% of new cases, underscoring that the challenge is not diminishing but instead consolidating in a smaller group of high-burden nations(1).

The prolonged treatment duration, alongside the risks of transmission and social stigma, makes TB treatment adherence and control a complex public health challenge that demands sustained behavioral and systemic interventions(8). Ensuring TB patients adhere to their treatment plan is critical to avoid serious complications and minimize the burden on the already strained healthcare system (9–12). Many new cases of Multi-drug Resistance Tuberculosis (MDR-TB) are created each year by a combination of physician error and poor patient adherence to treatment, transforming fully susceptible organisms, or those with less complex resistance patterns, into MDR-TB(13, 14).

The patient's knowledge of anti-TB treatment is identified as a strong factor that enables treatment adherence (8, 10, 11, 15). Accurate knowledge enables patients to make informed decisions, recognize the critical role of adherence, and actively manage their own health (8). Conversely, poor knowledge is associated with high transmission and poor treatment adherence (16). Hence, identifying and closing knowledge gaps improves attitudes and practices related to TB (17). Health education serves as the primary mechanism for this knowledge transfer, increasing awareness, strengthening health-related decision-making, and building skills necessary for treatment completion. (18, 19).

Knowledge is a necessary upstream determinant of treatment adherence shaping the perceptual foundations on which behavioral engagement depends. Patients who lack an accurate understanding of TB transmission, treatment rationale, and consequences of non-completion are less likely to perceive treatment as personally relevant or beneficial, creating a cognitive barrier that structural or motivational interventions alone cannot overcome (18, 20, 21), (22). Addressing these knowledge gaps requires scalable, accessible delivery mechanisms that can reach patients beyond clinic walls, a gap that innovative health interventions are uniquely positioned to fill.

The Health Belief Model (HBM) serves as the theoretical foundation for this study. The model posits that health behaviours are determined by individuals' perceptions of disease threat (perceived susceptibility and severity) and their evaluation of recommended actions (perceived benefits minus perceived barriers). Beyond

explaining health behaviour, the HBM provides a framework for evaluating the effectiveness of interventions through pre- and post-intervention assessments of these perceptual constructs (23, 24). Knowledge improvement directly targets the perceived susceptibility and perceived severity constructs of the HBM, the cognitive foundations upon which patients assess their personal risk and the severity of TB consequences. Without accurate knowledge, these perceptual constructs remain underdeveloped, limiting the model's downstream pathway toward health action.

Mobile Health (mHealth) interventions have been identified as a valuable and cost-effective tool for health education and promoting treatment adherence among patients (25). In Low- and Middle-Income Countries (LMICs), mHealth offers a strategic intervention medium with potential to improve patient management across all age groups and socioeconomic backgrounds (26, 27)

mHealth can identify and address knowledge gaps regarding TB, which is essential to advancing the End TB Strategy's transformative agenda (28). Mobile health platforms have demonstrated feasibility in low-resource African health contexts, with SMSaúde in Mozambique showing that structured remote communication can be implemented within existing health system constraints thereby establishing a foundation for knowledge-focused interventions, while single-mode reminders (SMS or Phone-calls) have shown effectiveness in improving treatment outcomes, (29)(30), emerging evidence suggests that multifaceted mHealth approaches may offer complementary benefits, though their specific impact on TB knowledge domains warrants further investigation(25).

Despite growing evidence for mHealth interventions in TB management globally, comparative evidence on the effectiveness of SMS versus phone-call approaches and their combined use remains limited in Nigeria, where the burden is high and contextual factors may significantly shape intervention response. This study addresses that gap by evaluating the comparative and combined effectiveness of SMS and phone-call interventions on TB knowledge among patients in Lagos State, using the Health Belief Model as a framework to understand how improved knowledge shapes the perceptual determinants of treatment engagement.

METHODS

This paper presents findings on TB knowledge outcomes from a quasi-experimental longitudinal study whose full methodology, including study design, sampling procedures, intervention protocols, and instrumentation, has been published in a companion paper (31). Briefly, sample size was estimated based on a 20 percentage-point difference in treatment adherence proportions between control (60%) and intervention arms (80%) (Cohen's $h \approx 0.45$) (32), requiring a minimum of 25 participants per arm at 90% power ($\alpha = 0.05$), inflated to 32 per arm to allow for 20% attrition, as detailed in the companion paper. Post-hoc ICC verification ($p = 0.388$, 95% CI: 0.279–0.496) confirmed that the achieved sample of 32 per arm was adequate for the longitudinal repeated-measures design. A summary of the key methodological parameters relevant to the present analysis is provided in Table I.

Descriptive statistics were used to summarise participant characteristics and the distribution of outcome variables across the three data collection points: baseline, midline (6 weeks), and follow-up. For inferential analysis, knowledge scores were dichotomised into high and low categories using the median at each time

point as the threshold, with scores at or above the median classified as high. The median knowledge score was consistent across all three time points (baseline, midline, and follow-up: 15, 15, and 15, respectively).

Given the non-normal data distribution, for inferential analysis, we employed Generalized Estimating Equations (GEE) with robust standard errors to account for within-subject correlation across the three time points. Models were specified with a binomial distribution and a logit link, included intervention, time, and their interaction as fixed effects (control group and baseline as references), and used an unstructured working correlation matrix selected by Quasi-likelihood under Independence Criterion (QIC). Results are presented as odds ratios with 95% confidence intervals and Wald p-values ($\alpha = 0.05$).

Although participants could not be blinded to their intervention assignment due to the nature of the SMS and phone-call delivery, outcome assessors and data analysts were blinded to group allocation during data cleaning and analysis.

Table 1
Summary of Study Design and Methods

Parameter	Details
Study design	Quasi-experimental longitudinal study with four arms
Setting	12 DOTS centres across four LGAs in Lagos State, Nigeria (Ikorodu, Alimosho, Ajeromi, Lagos Mainland)
Participants	128 adults on DOTS therapy for laboratory-confirmed TB; 32 per arm; zero attrition
Intervention arms	Arm 1: SMS every other day; Arm 2: Bi-weekly Phone-calls; Arm 3: SMS + Phone-calls combined; Arm 4: Standard care (control)
Data collection	Three time points – baseline, 6th week (midline), and 12th week follow-up (February–May 2023)
Primary outcome	TB Knowledge (Cronbach's $\alpha = 0.72$), dichotomised as high ($\geq$ median score of 15) or low at each time point
Covariates	Age category and education level
Statistical method	Generalized Estimating Equations (GEE); binomial distribution, logit link, unstructured working correlation matrix; results reported as odds ratios (OR) with 95% CI and Wald p-values ($\alpha = 0.05$)
Full methods	Uwalaka et al (31). International Journal of Public Health and Pharmacology, 6(1), 35–58. https://doi.org/10.52589/IJPHP-NFA8S2SD

The eligibility criteria were consistent with those in the companion paper. Inclusion criteria were: residence in Lagos State, ≥ 30 days on DOTS therapy for laboratory-confirmed TB, age ≥ 18 years, non-pregnant, and provision of written informed consent. Exclusion criteria included non-DOTS patients, drug-resistant TB, and patients who were too ill to participate at the time of recruitment.

Intervention fidelity was supported through standardized procedures. SMS delivery receipts were monitored, and phone calls were made by trained research assistants using structured scripts, as detailed in the companion paper.

All analyses were done using IBM SPSS Statistics version 21. Non-normality of the Knowledge distribution was confirmed prior to analysis (Table 2).

Table 2
Test of Normality for Knowledge

Tests of Normality						
Kolmogorov-Smirnov ^a			Shapiro-Wilk			
	Statistic	d.f	Sig.	Statistic	d.f	Sig.
Knowledge	0.19	128	.000	0.83	128	.000
<i>a. Lilliefors Significance Correction</i>						

a. Lilliefors Significance Correction

As a pre-specified secondary analysis, the association between TB knowledge and medication adherence was examined using two complementary approaches. First, Spearman rank correlation coefficients were computed to assess the cross-sectional relationship between TB knowledge and medication adherence at each of the three data collection points : baseline, midline (6th week), and 12th-week follow-up. Spearman's correlation was selected, consistent with the non-parametric approach adopted for the primary analysis, given the confirmed non-normality of the outcome distributions. Correlations were computed as two-tailed tests with statistical significance set at $\alpha = 0.05$.

Second, a separate GEE model was estimated with medication adherence as the outcome, incorporating TB knowledge as a time-varying covariate, along with intervention type, time, age category, and education level. This model was specified using the same analytical framework as the primary GEE model binomial distribution, logit link function, unstructured working correlation matrix selected by QIC, and robust sandwich standard errors to ensure comparability of estimates across the two models. The control group and baseline time point served as reference categories. Results are reported as odds ratios with 95% confidence intervals and Wald p-values at $\alpha = 0.05$.

Covariate selection for the GEE models was guided by baseline logistic regression analysis conducted on the full study sample of 128 participants prior to the intervention, using the Enter method with sex, age category, marital status, employment status, education level, and religion entered simultaneously as predictors of baseline TB knowledge. Age category emerged as the only statistically significant independent predictor of baseline knowledge (overall Wald $\chi^2 = 10.01$, $df = 2$, $p = 0.007$). Participants aged 31–45 years had 82% lower odds of high knowledge compared to those aged ≥ 46 years (OR = 0.18, 95% CI: 0.06–0.52, $p < 0.001$), and those aged 18–30 years had 68% lower odds (OR = 0.32, 95% CI: 0.11–0.91, $p = 0.033$). Although education level did not reach statistical significance overall (Wald $\chi^2 = 1.76$, $df = 3$, $p = 0.623$), a counterintuitive descriptive pattern was observed whereby tertiary-educated participants recorded a higher proportion of low baseline knowledge scores (14.8%) than high scores (10.9%), warranting its retention as a precautionary covariate. Sex, marital status, employment status, and religion were not significant predictors of baseline TB knowledge (all $p > 0.05$) and were excluded from the covariate set to preserve model parsimony and reduce

overfitting risk. Accordingly, age category and education level were retained as covariates in subsequent GEE models (Table 3)

Table 3

Baseline Binary Logistic Regression – Demographic Predictors of TB Knowledge (N = 128) Model: $\chi^2(10) = 17.29$, $p = 0.068$; Nagelkerke $R^2 = 0.167$; Hosmer-Lemeshow $p = 0.420$; Classification accuracy: 66.4%

Variable	B	SE	Wald χ^2	df	p	OR	95% CI
Sex							
Male vs Female	-0.05	0.43	0.01	1	0.910	0.95	0.41–2.22
Age category ‡							
Overall	—	—	10.01	2	0.007	—	—
18–30 vs ≥ 46 years *	-1.15	0.54	4.54	1	0.033	0.32	0.11–0.91
31–45 vs ≥ 46 years **	-1.70	0.54	10.02	1	< 0.001	0.18	0.06–0.52
Marital status							
Married vs not married	0.64	0.43	2.22	1	0.136	1.90	0.82–4.42
Education level †							
Overall	—	—	1.76	3	0.623	—	—
Employment status							
Overall	—	—	0.55	2	0.759	—	—
Religion							
Christian vs Muslim	0.44	0.41	1.16	1	0.282	1.55	0.70–3.45
Note. Bold p-values = statistically significant ($p < 0.05$). Reference categories: Female (sex); ≥46 years (age); Not married (marital status); No education (education); Unemployed (employment); Muslim (religion).							

‡ Age category: retained as primary covariate – only statistically significant predictor of baseline TB knowledge (overall $p = 0.007$). † Education level: retained as precautionary covariate despite non-significance ($p = 0.623$) due to counterintuitive descriptive pattern – tertiary-educated participants recorded a higher proportion of low knowledge scores (14.8%) than high scores (10.9%), contrary to expected direction.

* $p < 0.05$ ** $p < 0.001$ Variables excluded from GEE covariate set: sex, marital status, employment status, religion . (all $p > 0.05$). Age category and education level were retained as covariates in all subsequent GEE models.

This secondary analysis was conducted to examine whether improvement in TB knowledge, the primary intervention target, was associated with concurrent improvements in medication adherence, and whether knowledge independently predicted adherence after accounting for intervention exposure and time. Given that the Baron and Kenny prerequisite conditions for formal mediation analysis, specifically the requirement that the mediator significantly predicts the outcome in the fully adjusted model, were not met, (33) mediation

analysis was not pursued. Instead, the knowledge-adherence relationship is reported descriptively and longitudinally as a secondary finding, with interpretation guided by the Health Belief Model pathway linking upstream cognitive change to downstream behavioral engagement.

This study was conducted in accordance with the ethical principles of the Declaration of Helsinki. Ethical approvals were obtained from Babcock University Health Research Committee (BUHREC/00G/23) and Lagos University Teaching Hospital Research Ethics Committee (LUTHREC ADM/DSCST/HREC/APP/5657). Administrative approvals were obtained from the Lagos State Ministry of Health (LSMOH) and the Lagos State Primary Health Care Board (LSPHCB). Written informed consent was obtained from all participants prior to enrolment. Participants were assured of confidentiality and informed of their right to withdraw from the study at any time without consequences. All data were anonymised and stored securely.

RESULTS

Descriptive Findings

No attrition was recorded during the study period; all study participants completed all three data collection points. A total of 128 participants were included in the study, with 32 participants allocated to each arm. There were more male participants (81, 63.30%) than female participants (47, 36.70%) overall. The SMS group had 68.80% males, the phone-call group 59.40%, the combined SMS and phone-call group 59.40%, and the control group 65.60%. The mean age for all groups combined was 35.68 ± 11.07 years, with the phone-call arm recording the highest mean age (38.28 ± 10.84 years). Regarding marital status, the majority were married (75, 58.60%), followed by single (51, 39.80%), and a small proportion were divorced or separated (2, 1.60%). Most participants held secondary education (74, 57.80%), followed by tertiary (33, 25.80%). Occupationally, 75 participants (58.60%) were self-employed, 26 (20.30%) were employed, and 27 (21.10%) were unemployed. In terms of religion, 77 participants (60.20%) identified as Christians and 51 (39.80%) as Muslims (Table 4).

Table 4
Socio-demographic Characteristics of Participants for all Study Groups

Variables	SMS N (%)	Phone-call N (%)	SMS and Phone-call N (%)	Control N (%)	Total N (%)
Sex					
Male	22 (68.80)	19 (59.40)	19 (59.40)	21 (65.60)	81 (63.30)
Female	10 (31.30)	13 (40.60)	13 (40.60)	11 (34.40)	47 (36.70)
Age					
18–30 years	3 (9.40)	22 (68.80)	23 (71.90)	3 (9.40)	51 (39.84)
31–45 years	12 (37.50)	9 (28.10)	6 (18.80)	18 (56.30)	45 (35.15)
46 years and above	17 (53.10)	1 (3.10)	3 (9.40)	11 (34.40)	32 (25.00)
Mean age $\pm$ SD	34.31 $\pm$ 12.98	38.28 $\pm$ 10.84	35.31 $\pm$ 9.71	34.81 $\pm$ 10.57	35.68 $\pm$ 11.07
Marital Status					
Married	15 (46.90)	21 (65.60)	17 (53.10)	22 (68.75)	75 (58.59)
Single	17 (53.10)	11 (34.40)	13 (40.60)	10 (31.25)	51 (39.84)
Divorced/Separated	0 (0.00)	0 (0.00)	2 (6.30)	0 (0.00)	2 (1.56)
Level of Education					
None	0 (0.00)	2 (6.30)	1 (3.10)	1 (3.10)	4 (3.10)
Primary	0 (0.00)	8 (25.00)	0 (0.00)	9 (28.10)	17 (13.30)
Secondary	28 (87.50)	17 (53.10)	15 (46.90)	14 (43.80)	74 (57.80)
Tertiary	4 (12.50)	5 (15.60)	16 (50.00)	8 (25.00)	33 (25.80)
Employment Status					
Self-employed	18 (56.30)	25 (78.10)	16 (50.00)	16 (50.00)	75 (58.60)
Employed	5 (15.60)	5 (15.60)	6 (18.80)	10 (31.30)	26 (20.30)
Unemployed	9 (28.10)	2 (6.30)	10 (31.30)	6 (18.80)	27 (21.10)
Religion					
Christianity	18 (56.30)	22 (68.80)	23 (71.90)	14 (43.80)	77 (60.20)
Islam	14 (43.80)	10 (31.30)	9 (28.10)	18 (56.30)	51 (39.80)

Knowledge scores showed a consistent upward trend over time across all intervention groups (Table 5) presents the distribution of knowledge scores across intervention groups and time points. At baseline, the proportion of participants with high knowledge ranged from 28.1% in the combined phone + SMS group to 81.3% in the Phone-call group. By the 12th-week follow-up, the phone-only group achieved the highest

proportion of high knowledge (93.8%), followed by the SMS-only group (75.0%), the control group (59.4%), and the combined phone + SMS group (50.0%). All groups showed improvement over time, with the control group increasing by 25 percentage points, suggesting a natural learning effect or the impact of standard care. However, the combined intervention consistently underperformed relative to both single-modality interventions throughout the study period.

Table 5
Changes in Knowledge across Baseline, 6th Week Post Intervention, and 12th Week Evaluation Phases by Intervention Type

Intervention	Baseline	6th Week	12th Week Follow-up
	High / Low n (%)	High / Low n (%)	High / Low n (%)
SMS Only (n = 32)	22 (68.8) / 10 (31.2)	23 (71.9) / 9 (28.1)	24 (75.0) / 8 (25.0)
Phone-call (n = 32)	26 (81.3) / 6 (18.8)	28 (87.5) / 4 (12.5)	30 (93.8) / 2 (6.3)
Phone + SMS (n = 32)	9 (28.1) / 23 (71.9)	10 (31.3) / 22 (68.8)	16 (50.0) / 16 (50.0)
Control (n = 32)	11 (34.4) / 21 (65.6)	13 (40.6) / 19 (59.4)	19 (59.4) / 13 (40.6)
Total (N = 128)	68 (53.1) / 60 (46.9)	74 (57.8) / 54 (42.2)	89 (69.5) / 39 (30.5)

INFERENCE FINDINGS

As specified in the Methods, GEE models were used to examine longitudinal changes in TB knowledge across the three time points, adjusting for age category and education level. An unstructured working correlation matr9 was retained based on optimal QIC values.

Model Effects

The adjusted GEE model demonstrated that both intervention type (Wald $\chi^2 = 46.30$, $p < 0.001$) and time (Wald $\chi^2 = 13.07$, $p = 0.001$) were statistically significant predictors of TB knowledge. Age category (Wald $\chi^2 = 0.30$, $p = 0.585$) and education level (Wald $\chi^2 = 2.28$, $p = 0.131$) were not significant predictors, indicating that knowledge differed across intervention groups and time points but was not independently associated with age or education after adjustment (Table 6).

Using the control group as the reference category, participants who received phone-call reminders had significantly higher odds of achieving high TB knowledge ($B = 2.22$, $SE = 0.42$, $p < 0.001$, $OR = 9.24$). Participants who received SMS reminders also had significantly higher odds ($B = 1.30$, $SE = 0.42$, $p = 0.002$, $OR = 3.67$). In contrast, the combined phone-call plus SMS intervention did not demonstrate a statistically significant difference compared with the control group ($B = -0.49$, $SE = 0.38$, $p = 0.197$, $OR = 0.61$), indicating that the combination of modalities conferred no additional benefit over standard care for improving knowledge (Table 6).

Estimated marginal means (EMMs) were 0.88 for the phone-call group, 0.75 for the SMS group, 0.45 for the control group, and 0.33 for the phone-call plus SMS group. Notably, the predicted probability of high knowledge

in the combined intervention arm was lower than that of the control group, a finding consistent with cognitive load effects when multiple concurrent communication channels are deployed simultaneously.

Time was a statistically significant predictor of knowledge (Wald $\chi^2 = 13.07$, $p = 0.001$). At 12th week follow-up, participants had significantly higher odds of achieving high knowledge compared with baseline ($B = 0.87$, $SE = 0.26$, $p = 0.001$, $OR = 2.38$). The difference between the 6th week and baseline did not reach statistical significance ($B = 0.24$, $SE = 0.24$, $p = 0.324$, $OR = 1.27$), suggesting that knowledge gains accumulated predominantly over the full intervention period rather than emerging during the early midline phase.

Table 6
Generalized Estimating Equation (GEE) Results for Knowledge across Time and Intervention Groups

Effects	Parameter	B	SE	Wald χ^2	p-value	Exp(B) [OR]	95% CI
Knowledge							
Intercept		-1.38	0.61	5.19	0.023	—	—
Intervention				46.30	< 0.001	—	—
	<i>Phone-call vs Control</i>	2.22	0.42	28.24	< 0.001	9.24	(4.07–20.99)
	<i>SMS vs Control</i>	1.30	0.42	9.80	0.002	3.67	(1.63–8.27)
	<i>Phone + SMS vs Control</i>	-0.49	0.38	1.67	0.197	0.61	(0.29–1.29)
Time				13.07	0.001	—	—
	<i>Follow-up vs Baseline</i>	0.87	0.26	11.46	0.001	2.38	(1.43–3.95)
	<i>6th week vs Baseline</i>	0.24	0.24	0.97	0.324	1.27	(0.79–2.05)
	<i>Baseline (ref)</i>	0	—	—	—	1.00	—
Age		0.10	0.18	0.30	0.585	—	—
Education		0.50	0.33	2.28	0.131	—	—
<i>Note: All models include Age and Education as covariates. Bold text = significant p-value.</i>							

Age- and education-adjusted EMMs increased from 0.54 at baseline to 0.60 at 6th week, and further to 0.74 at 12th week follow-up. Bonferroni-adjusted pairwise comparisons showed a significant improvement from baseline to 12th week follow-up ($p = 0.003$) and from 6th week to 12th week follow-up ($p = 0.023$), whereas the difference between baseline and 6th week was not statistically significant ($p = 0.972$) (Table 7).

Pairwise comparisons between intervention groups revealed that phone-call alone was substantially more effective than the combined phone-call plus SMS intervention (mean difference = 0.55, $p < 0.001$), and SMS alone was also significantly more effective than the combined approach (mean difference = 0.42, $p < 0.001$). No significant difference was observed between the phone-call and SMS groups (mean difference = 0.13, $p = 0.402$), indicating comparable efficacy between the two single-modality interventions for knowledge outcomes.

Table 7
Estimated Marginal Means (EMM) and Pairwise Comparisons for Knowledge across Time and Intervention Groups

Outcome	Factor	Level / Comparison	Mean / Diff	SE	p (adj)	95% CI Lower	95% CI Upper
Knowledge – Intervention: Estimated Marginal Means							
Knowledge	Intervention	Phone-call	0.88	0.05	—	0.76	0.95
		SMS	0.75	0.08	—	0.56	0.87
		Phone + SMS	0.33	0.08	—	0.20	0.49
		Control	0.45	0.09	—	0.28	0.63
Knowledge – Intervention: Pairwise Comparisons							
		Phone-call vs Control	0.43	0.08	< 0.001	0.22	0.65
		SMS vs Control	0.30	0.09	0.005	0.07	0.54
		Phone + SMS vs Control	−0.12	0.09	1.000	−0.35	0.12
		Phone-call vs SMS	0.13	0.07	0.402	−0.06	0.33
		Phone-call vs Phone + SMS	0.55	0.07	< 0.001	0.36	0.74
		SMS vs Phone + SMS	0.42	0.09	< 0.001	0.18	0.65
Knowledge – Time: Estimated Marginal Means							
	Time	Baseline	0.54	0.08	—	0.38	0.70
		6th Week	0.60	0.08	—	0.44	0.74
		Follow-up (12th week)	0.74	0.06	—	0.60	0.84
Knowledge – Time: Pairwise Comparisons							
		Follow-up vs Baseline	0.20	0.06	0.003	0.05	0.34
		6th Week vs Baseline	0.06	0.06	0.972	−0.08	0.20
		Follow-up vs 6th Week	0.14	0.05	0.023	0.01	0.26
Note: Pairwise comparisons use Bonferroni correction. p (adj) = Bonferroni-adjusted p-value. Mean/Diff = estimated marginal mean (for EMMs) or mean difference Re(for pairwise comparisons).							

Secondary Analysis: Association Between TB Knowledge and Medication Adherence

As a pre-specified secondary analysis, Spearman rank correlations were conducted to examine the cross-sectional association between TB knowledge and medication adherence at each of the three data collection points. A separate GEE model was then estimated with medication adherence as the outcome, incorporating TB knowledge as a time-varying covariate alongside intervention type, time, age category, and education level, to examine whether knowledge independently predicted adherence in a longitudinal framework.

Correlation Findings

At baseline, a significant positive correlation was observed between TB knowledge and medication adherence ($r_s = 0.326$, $p < 0.001$), indicating that patients with higher TB knowledge scores were more likely to report higher medication adherence at study entry. This significant positive association persisted at midline ($r_s = 0.267$, $p = 0.002$), suggesting that the knowledge-adherence relationship was maintained during the active intervention period. However, by the 12th-week follow-up, the correlation between TB knowledge and medication adherence was no longer statistically significant ($r_s = 0.066$, $p = 0.457$), indicating that the association attenuated over the course of the study (Table 8).

Table 8
Spearman Rank Correlations Between TB Knowledge and Medication Adherence

Time Point	r_s	p-value	N
Baseline	0.326**	< 0.001	128
Midline (6th Week)	0.267**	0.002	128
Follow-up (12th Week)	0.066	0.457	128
** Correlation is significant at the 0.01 level (2-tailed). r_s = Spearman rank correlation coefficient. Knowledge = TB knowledge category; Adherence = medication adherence category (self-report).			

GEE Model 2 – Independent Effect of Knowledge on Medication Adherence

A separate GEE model was estimated with medication adherence as the outcome variable, incorporating TB knowledge as a time-varying covariate, along with intervention type, time, age category, and education level. Model fit was acceptable (QIC = 449.281, QICC = 446.606).

Model Effects

Intervention type remained a highly significant predictor of medication adherence after controlling for knowledge, time, age, and education (Wald $\chi^2 = 55.204$, $p < 0.001$), confirming that the intervention effect on adherence was not fully explained by knowledge improvement alone. Time was also a statistically significant overall predictor of adherence (Wald $\chi^2 = 7.182$, $p = 0.028$). Knowledge approached but did not reach conventional statistical significance as an independent predictor of medication adherence in the fully adjusted model ($B = 0.441$, $SE = 0.262$, Wald $\chi^2 = 2.842$, $p = 0.092$, $OR = 1.55$, 95% CI: 0.93–2.60), with a positive but non-significant directional effect. Age category (Wald $\chi^2 = 0.895$, $p = 0.344$) and education level (Wald $\chi^2 = 0.406$, $p = 0.524$) were not statistically significant predictors of medication adherence after adjustment (Table 9).

Intervention Effects on Medication Adherence

Using the control group as the reference category, participants who received phone-call reminders had significantly higher odds of achieving high medication adherence ($B = 2.443$, $SE = 0.415$, $p < 0.001$, $OR = 11.50$, 95% CI: 5.10–25.93). Participants who received SMS reminders also demonstrated significantly higher odds of adherence compared to the control group ($B = 2.432$, $SE = 0.368$, $p < 0.001$, $OR = 11.38$, 95% CI: 5.53–23.42). The combined phone-call plus SMS intervention similarly showed significantly higher odds of adherence relative to the control group, though with a substantially smaller effect ($B = 1.059$, $SE = 0.340$, $p = 0.002$, $OR = 2.88$, 95% CI: 1.48–5.61) (Table 9).

Estimated marginal means for medication adherence, adjusted for knowledge, age, and education, were 0.80 for the phone-call group, 0.80 for the SMS group, 0.51 for the combined group, and 0.26 for the control group. Pairwise comparisons confirmed that both phone-call and SMS interventions produced significantly higher predicted probabilities of high adherence than the control group ($p < 0.001$ for both) and significantly higher adherence than the combined arm (phone-call vs combined: mean difference = 0.30, $p = 0.008$; SMS vs combined: mean difference = 0.30, $p = 0.002$). No significant difference was observed between the phone-call and SMS groups for medication adherence (mean difference = 0.00, $p = 1.000$), indicating comparable efficacy between the two single-modality interventions for this outcome (Table 10).

Notably, the combined intervention demonstrated significantly higher predicted adherence than the control group (mean difference = 0.24, $p = 0.010$), distinguishing its adherence pattern from its knowledge pattern, where the combined arm fell below even the control group. This divergence suggests that the mechanisms through which the combined intervention influences knowledge and adherence may differ, with the combined approach retaining some adherence benefit despite its failure to improve knowledge above standard care levels. The odds ratios for phone-call and SMS interventions in the adherence model were notably larger than those observed in the primary knowledge model, particularly for the SMS arm ($OR = 11.38$ for adherence versus $OR = 3.67$ for knowledge), suggesting that SMS may exert a stronger influence on medication-taking behaviour than on knowledge acquisition, and that its adherence benefit operates through mechanisms beyond knowledge improvement alone.

Table 9
GEE Model 2 – Results for Medication Adherence with Knowledge as Time-Varying Covariate

Effects	Parameter	B	SE	Wald χ^2	p-value	OR	95% CI
Intercept		-1.577	0.598	6.951	0.008	—	—
Medication Adherence							
Intervention (Overall)				55.204	< 0.001	—	—
	Phone-call vs Control	2.443	0.415	34.595	< 0.001	11.50	(5.10–25.93)
	SMS vs Control	2.432	0.368	43.692	< 0.001	11.38	(5.53–23.42)
	Combined vs Control	1.059	0.340	9.685	0.002	2.88	(1.48–5.61)
	Control (ref)	0	—	—	—	1.00	—
Time (Overall)				7.182	0.028	—	—
	Follow-up vs Baseline	0.786	0.300	6.887	0.009	2.19	(1.22–3.95)
	6th Week vs Baseline	0.196	0.251	0.614	0.433	1.22	(0.74–2.00)
	Baseline (ref)	0	—	—	—	1.00	—
Age		-0.171	0.181	0.895	0.344	—	—
Education		0.206	0.323	0.406	0.524	—	—
Knowledge		0.441	0.262	2.842	0.092	1.55	(0.93–2.60)
Note: Control group and baseline serve as reference categories. Bold text = significant or borderline p-value. QIC = 449.281. All models include Age and Education as covariates.							

Time Effects on Medication Adherence

Age- and education-adjusted estimated marginal means for medication adherence increased progressively from 0.53 at baseline to 0.58 at midline and 0.71 at 12th-week follow-up. Bonferroni-adjusted pairwise comparisons revealed a statistically significant improvement in adherence from baseline to 12th-week follow-up (mean difference = 0.18, $p = 0.022$), mirroring the temporal trajectory observed for knowledge outcomes. The difference between baseline and midline was not statistically significant (mean difference = 0.05, $p = 1.000$), nor was the difference between midline and follow-up (mean difference = 0.13, $p = 0.125$), indicating that as with knowledge, meaningful adherence gains accumulated predominantly over the full 12-week intervention period rather than emerging during the early midline phase (Table 10).

Table 10
Estimated Marginal Means and Pairwise Comparisons for Medication Adherence

Outcome	Factor	Level / Comparison	Mean / Diff	SE	p (adj)	95% CI Lower	95% CI Upper
Medication Adherence — Intervention: Estimated Marginal Means							
Medication Adherence	Intervention	Phone-call	0.80	0.069	—	0.63	0.91
		SMS	0.80	0.070	—	0.63	0.91
		Phone + SMS	0.51	0.097	—	0.32	0.69
		Control	0.26	0.075	—	0.14	0.43
Medication Adherence — Intervention: Pairwise Comparisons							
		Phone-call vs Control	0.54	0.072	< 0.001	0.35	0.73
		SMS vs Control	0.54	0.064	< 0.001	0.37	0.71
		Combined vs Control	0.24	0.078	0.010	0.04	0.45
		Phone-call vs SMS	0.00	0.067	1.000	-0.17	0.18
		Phone-call vs Combined	0.30	0.092	0.008	0.05	0.54
		SMS vs Combined	0.30	0.081	0.002	0.08	0.51
Medication Adherence — Time: Estimated Marginal Means							
	Time	Baseline	0.53	0.087	—	0.36	0.69
		6th Week	0.58	0.095	—	0.39	0.75
		Follow-up (12th Week)	0.71	0.077	—	0.54	0.84
Medication Adherence — Time: Pairwise Comparisons							
		Follow-up vs Baseline	0.18	0.068	0.022	0.02	0.35
		6th Week vs Baseline	0.05	0.061	1.000	-0.10	0.20
		Follow-up vs 6th Week	0.13	0.066	0.125	-0.02	0.29
Note: Pairwise comparisons use Bonferroni correction. p (adj) = Bonferroni-adjusted p-value. Mean/Diff = estimated marginal mean (for EMMs) or mean difference (for pairwise comparisons). All models adjust for Age, Education, and Knowledge as covariates. Bold text = significant p-value.							

Discussion

This investigation evaluated the effectiveness of structured mHealth interventions in enhancing tuberculosis knowledge among patients undergoing DOTS therapy in Lagos State, Nigeria. The findings reveal a clear hierarchy of intervention effectiveness: phone-call reminders produced the largest knowledge gains, SMS reminders yielded moderate improvements, and, contrary to expectations, combining both modalities resulted in no measurable benefit over standard care. These results challenge the assumption that multimodal communication strategies inherently outperform single-channel approaches, instead suggesting that the quality, timing, and interactivity of communication may outweigh simple message volume.

Comparative Effectiveness of Communication Modalities

The superiority of phone-call interventions in improving TB knowledge aligns with communication theory distinctions between synchronous and asynchronous information exchange. Synchronous voice communication enables real-time clarification, adaptive questioning, and personalized feedback mechanisms that facilitate deeper cognitive processing and knowledge consolidation (34, 35). Within the Health Belief Model framework, this interactive format is particularly suited to addressing the perceptual constructs that underpin health behaviour. Phone conversations allow providers to gauge patients' existing understanding, identify misconceptions, and tailor explanations to individual circumstances, thereby strengthening perceived susceptibility and severity in ways that standardized messaging cannot replicate.

While Akamike et al., (36) demonstrated that mobile messaging significantly improved TB knowledge among Nigerian patients, our study extends these findings by showing that synchronous Phone-calls are significantly more effective than SMS (OR = 9.24 vs. OR = 3.67) and that combining modalities can be counterproductive. The moderate but significant effectiveness of SMS interventions, while less potent than Phone-calls, remains noteworthy for its practical implications. Text messaging offers a scalable, low-cost alternative that can reach patients across geographic and economic barriers (37). The fact that SMS achieved meaningful knowledge gains despite its asynchronous, one-way nature suggests that even basic text-based education can effectively convey core TB information when structured appropriately. This finding is consistent with that of Valizadeh et al., (38) where sms based education improved mothers' sleep knowledge and that of Aigbonoga et al., (39) where there was a significant increase in stroke-prevention knowledge. Our findings on the effectiveness of SMS reminders for TB knowledge and adherence align with continental priorities, as demonstrated by the Africa CDC's ongoing initiative evaluating SMS messaging to strengthen TB treatment in Ethiopia and Liberia (40). This convergence between our empirical results and Africa CDC's strategic direction underscores the potential to scale SMS-based interventions across the continent, particularly in areas where mobile phone penetration is high, but health system resources remain constrained.

The Counterintuitive Failure of Combined Interventions

The underperformance of the combined SMS-plus-phone-call intervention represents the study's most unexpected finding. As noted, the combined arm's EMMs fell below those of the control group, a pattern requiring theoretical explanation. This result directly contradicts the intuitive appeal of "more is better" intervention design and carries important implications for mHealth programme development.

Several theoretical frameworks help explain this counterintuitive pattern. Cognitive load theory posits that learners possess finite cognitive resources for processing new information; exceeding these limits through redundant or overlapping content can impede rather than facilitate knowledge acquisition (41). In the combined arm, participants received bi-weekly Phone-calls and SMS messages every two days, often covering similar educational content. This delivery schedule may have created informational redundancy that exhausted patients' cognitive capacity for meaningful engagement, particularly among individuals already managing the demands of chronic illness treatment.

An alternative explanation lies in the concept of message fatigue. Health communication research has demonstrated that repeated exposure to similar content, particularly across multiple channels, can lead to diminishing returns and even active disengagement (42). For patients receiving TB treatment, who already face daily medication requirements and regular clinic visits, the addition of frequent, overlapping reminders may be perceived as burdensome rather than supportive. This pattern is consistent with established digital health engagement research showing that delivering overlapping content through multiple channels without adaptive tailoring can trigger early disengagement, particularly when redundant messaging exhausts users' cognitive capacity for meaningful interaction (43–45). The finding is contradictory to that of Yang and Van Stee (27), where combining a mobile phone with another type of media was significantly higher than in interventions that used a mobile phone only to improve health outcomes.

The design of the MILEAGE4TB trial (46), which similarly compares SMS-alone, telephone-calls-alone, and combined modalities for TB outcomes in Uganda, reflects the broader recognition that multimodal approaches require rigorous evaluation before programmatic adoption a concern our findings now empirically substantiate.

Temporal Dynamics of Knowledge Change

The temporal pattern of knowledge improvement across all groups revealed that significant gains emerged only at the 12-week follow-up, with no statistically significant change at midline. This pattern diverges from studies reporting early knowledge improvements following mHealth interventions (16) and suggests that durable TB knowledge consolidation requires sustained, spaced exposure rather than brief intervention periods. The finding aligns with educational psychology principles that meaningful learning, particularly of complex health information, requires repeated reinforcement over extended timelines (19).

This delayed emergence of knowledge effects carries important methodological implications for mHealth research. Studies employing short follow-up periods may underestimate the true impact of educational interventions by capturing only immediate recall rather than consolidated learning. For tuberculosis programs, this finding suggests that knowledge-focused mHealth interventions should be maintained throughout the full treatment course rather than limited to initial phase (47).

The Divergent Relationship Between Knowledge and Adherence

The secondary analysis examining the knowledge-adherence relationship revealed a progressively attenuating association over the study period. While baseline and midline correlations were statistically significant, this relationship had dissipated by the 12-week follow-up. Moreover, when knowledge was modelled as a time-

varying predictor of adherence while accounting for intervention effects, it approached but did not reach conventional statistical significance ($p = 0.092$).

This pattern suggests that knowledge may serve as an enabling factor for adherence during early treatment phases but becomes less determinative as patients gain direct experience with treatment routines. Patients may transition from cognitively driven adherence (based on understanding of disease and treatment) to behaviorally driven adherence (based on habit formation and practical integration of medication-taking into daily routines) as treatment progresses (11). The strong persistence of intervention effects on adherence after controlling for knowledge (Wald $\chi^2 = 55.204$, $p < 0.001$) further indicates that mHealth interventions improve adherence through mechanisms that operate independently of knowledge enhancement (48).

This interpretation carries important theoretical implications for the application of the Health Belief Model in mHealth research. The HBM explicitly acknowledges that health behaviours are shaped not only by perceptions of susceptibility, severity, benefits, and barriers but also by cues to action which may include social support, structural enablers, and external reminders and by modifying factors such as demographic, sociopsychological, and structural variables (23, 24). In this study, the observed attenuation of the knowledge-adherence relationship over time, alongside the persistence of strong intervention effects even after controlling for knowledge, suggests that the mHealth interventions may have operated through multiple pathways within the HBM framework. Beyond their educational content, Phone-calls and SMS reminders served as direct cues to action within the HBM framework, prompting medication-taking behaviours through repeated external contact. This sustained engagement may also have reinforced patients' self-efficacy and deepened their perception of the benefits of treatment completion. These observations align with evidence from comparable settings (49, 50) and collectively underscore a broader principle: effective mHealth interventions are not merely delivery mechanisms but behavioral activation tools that must be deliberately designed to engage the full spectrum of HBM constructs as outlined above. The importance of theory-driven intervention design is underscored by Sazali et al., (51) who note that digital tools in TB care are most effective when deliberately integrated with behavioral frameworks such as the HBM, rather than deployed as standalone technical solutions.

Implications for Programme Design and Policy

The superiority of phone-call interventions across knowledge provides strong evidence for integrating structured voice-based follow-up into routine tuberculosis services. Where workforce capacity or cost constraints preclude Phone-calls for all patients, SMS reminders represent a viable alternative that delivers meaningful, cost-effective benefits. However, the underperformance of the combined approach carries an important cautionary message: adding communication channels does not automatically improve outcomes and may actively undermine knowledge acquisition.

Tuberculosis programmes should therefore resist the intuitive assumption that "more contact equals better outcomes." Instead, intervention design should prioritize communication quality, personalization, and appropriate frequency over message volume. Structured call scripts should be designed to assess and address patient knowledge gaps, correct misconceptions, and reinforce key educational messages through interactive dialogue. For SMS interventions, content should be carefully sequenced to avoid redundancy and spaced to support sustained engagement rather than overwhelming patients with frequent, overlapping messages.

The finding that knowledge improvement was not a prerequisite for adherence gains suggests that programmes need not delay adherence-focused interventions until knowledge deficits are fully addressed. Rather, mHealth strategies can pursue adherence support and health education as parallel, mutually reinforcing objectives. Digital tools at DOTS facilities should be used to track baseline knowledge gaps and tailor intervention content accordingly, moving toward a more personalized model of mHealth delivery as infrastructure allows.

Study Limitations

This study's strengths include its longitudinal design, four-arm comparison, zero attrition, and use of robust analytical methods appropriate for non-normal data. The inclusion of a secondary analysis examining knowledge-adherence relationships adds theoretical depth to the primary findings.

Several limitations warrant consideration. The study was confined to Lagos State, which may limit generalizability to other regions with different cultural, linguistic, and health system contexts. The exclusion of non-English speakers may introduce selection bias, as the findings may not fully represent patients with limited English literacy. Knowledge was measured using a structured questionnaire that, while validated, may not capture all dimensions of TB understanding relevant to patient decision-making. The relatively short 12-week follow-up period may underestimate the full trajectory of knowledge consolidation. Although GEE models adjusted for age and education, the substantial baseline knowledge imbalance across arms (28.1%–81.3%), arising from LGA-level allocation, was not directly controlled for and may partly confound the observed intervention effects. Regarding the combined intervention, the null finding (OR = 0.61, 95% CI: 0.29–1.29) should be interpreted cautiously. The wide confidence interval reflects imprecision due to the sample size, which was powered to detect medium-to-large effects (e.g., phone call OR = 9.24) but not smaller or negative effects.

Future Research Directions

Future studies should examine whether the differential effectiveness of communication modalities persists across longer follow-up periods and different patient populations. Research is needed to identify the specific features of phone-call interventions that drive knowledge gains whether personalization, interactivity, duration, frequency, or some combination to inform more efficient intervention designs. The cognitive mechanisms underlying the combined arm's underperformance warrant further investigation, including whether informational redundancy, message fatigue, or other factors explain this pattern. Finally, studies incorporating objective measures of knowledge (e.g., standardized assessments) alongside self-report measures would strengthen evidence for mHealth effectiveness.

Results from the MILEAGE4TB RCT (46), currently underway in Uganda with over 2,300 participants, will offer important complementary evidence on whether our findings generalise across sub-Saharan African contexts with different health system structures

Conclusion

This study demonstrates that structured phone-call and SMS interventions significantly improve tuberculosis knowledge among patients in Nigeria, with Phone-calls producing the largest effects. The counterintuitive

underperformance of the combined intervention has important implications for how mHealth programmes are designed and evaluated. The progressive attenuation of the knowledge-adherence relationship over time indicates that knowledge serves as an enabling factor for early treatment engagement but may become less determinative as patients develop routine adherence behaviours. Tuberculosis programmes should prioritize interactive phone-based follow-up where feasible, use SMS as a scalable alternative, and resist the intuitive but counterproductive practice of combining multiple communication channels without clear evidence of additive benefit.

Declarations

Author Contribution

C.H.U, D.A, I.O.A, A.A.A, G.C.N, V.I.N.I, and S.O.D contributed to the conceptualization of the study. C.H.U, D.A, I.O.A, A.A.A, G.C.N, and A.H.A developed the methodology. C.H.U, S.N.O, and O.R.O performed the formal analysis. C.H.U, V.I.N.I, O.I.F, and S.N.O were responsible for data curation. C.H.U, D.A, I.O.A, and A.A.A wrote the original draft of the manuscript. C.H.U, G.C.N, V.I.N.I, S.O.D, O.I.F, S.N.O, A.H.A, and O.R.O reviewed and edited the manuscript. All authors read and approved the final manuscript and agree to be accountable for all aspects of the work.

Data Availability

The datasets used and analysed during the current study available from the corresponding author on reasonable request. All data analysed during this study are included in this published article.

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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