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Modeling Healthcare 4.0 Pathways to Effective and Efficient Universal Health Coverage for Neglected Tropical Diseases in Nigeria

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Abstract *Healthcare 4.0 technologies are increasingly recognized for their potential to strengthen Universal Health Coverage (UHC), yet the mechanisms through which they influence UHC performance for Neglected Tropical Diseases (NTDs) in resource-constrained settings remain insufficiently modeled. This study develops and empirically tests a socio-technical framework linking Healthcare 4.0 enablers, contextual conditions, and two key UHC performance dimensions, effectiveness and efficiency, in Nigeria. Primary data were collected from 314 experts across NTD, UHC, and digital health domains. A sequential analytical approach was implemented, including Principal Components Analysis, Confirmatory Factor Analysis, and Structural Equation Modeling. The final model demonstrated strong fit (RMSEA = 0.028; SRMR = 0.043; CFI = 0.99; NNFI = 0.99; χ^2/df = 1.24), with all structural paths statistically significant ($p < 0.001$). Two distinct but complementary pathways were identified. Technologies that enable continuous data exchange, ongoing monitoring, and enhanced clinical care, such as cloud computing and the Internet of Things, show stronger associations with effectiveness. In contrast, governance-oriented and computational infrastructures, including blockchain systems and big data analytics, are more closely linked to efficiency. The strength of these relationships varies depending on institutional readiness and broader system alignment. Collectively, the findings position Healthcare 4.0 as an integrated system driver whose effects are pathway-specific and context-dependent. The study provides an empirically grounded basis for designing coordinated digital health strategies aimed at strengthening UHC for NTDs in resource-constrained settings.*

Keywords *Digital Health Transformation, Healthcare 4.0, Neglected Tropical Diseases, Nigeria, Structural Equation Modeling, Universal Health Coverage.*

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Introduction

Neglected Tropical Diseases (NTDs) remain a major public health concern in Nigeria, which carries the largest NTD burden in sub-Saharan Africa. An estimated 138 million people were at risk in 2024, reflecting the scale and persistence of these conditions across the country [1, 2, 28]. Although Nigeria has established policy frameworks for both NTD control and Universal Health Coverage (UHC), implementation continues to fall short [2, 28, 29]. Service delivery remains fragmented, monitoring systems are weak, and coordination across institutions is often inconsistent [2, 3]. These limitations point to structural challenges beyond resource constraints, including system integration, real-time visibility, and operational coherence.

Recent evidence from Africa indicates that substantial progress has been achieved through regional NTD control and elimination programs; however, persistent challenges related to surveillance, coordination, financing, and health-system integration continue to limit sustainable elimination efforts. Lessons from these programs emphasize the need for stronger digital infrastructure and integrated health-system approaches capable of supporting real-time monitoring, resource allocation, and programmatic decision-making [27].

Healthcare 4.0 has emerged as a potential pathway for addressing these systemic weaknesses. Built on the convergence of Industry 4.0 technologies with healthcare delivery, Healthcare 4.0 emphasizes interconnected, data-driven, and responsive systems [4]. Technologies such as the Internet of Things (IoT), blockchain, cloud computing, big data analytics, artificial intelligence, and body sensors offer new opportunities to strengthen surveillance and improve coordination across levels of care [5, 6, 16]. However, their application within UHC systems for NTDs remains limited, often confined to isolated initiatives rather than integrated strategies [7].

Much of the existing literature focuses on individual technologies or high-income contexts, with relatively limited attention to integrated frameworks suited to low- and middle-income countries [8, 9]. In addition, UHC performance is frequently treated as a single outcome, without distinguishing between effectiveness and efficiency or examining how contextual conditions shape technological impact [10]. This creates an important gap in understanding the mechanisms through which Healthcare 4.0 influences performance. Recent studies further emphasize that the transition toward Healthcare 4.0 requires not only technological adoption but also organizational transformation and workforce digital readiness [11]. The digital transformation of healthcare has accelerated globally, particularly following the COVID-19 pandemic, which highlighted the importance of connected, data-driven, and resilient health systems capable of supporting continuity of care and rapid decision-making [18]. At the same time, advances in artificial intelligence and human-machine collaboration are increasingly shaping the future of healthcare delivery, creating new opportunities for enhanced diagnostics, predictive analytics, and personalized care [19]. These developments further reinforce the strategic relevance of Healthcare 4.0 technologies for strengthening health-system performance and advancing UHC objectives. Recent African evidence has similarly highlighted the importance of integrated systems approaches for sustaining NTD elimination gains, particularly through improved surveillance, coordination mechanisms, and data-driven decision-making [27]. Despite these advances, empirical models linking Healthcare 4.0 technologies to UHC performance for NTDs remain scarce.

Drawing on Healthcare 4.0, UHC, and NTD literature [4-15], this study adopts a socio-technical perspective in which digital technologies operate within a broader system of institutional, regulatory, and socio-economic

interactions. Within this framework, Healthcare 4.0 is conceptualized as an integrated system driver, whose impact depends on alignment with contextual conditions and whose effects are expressed through distinct performance pathways.

Research Objectives

The primary objective of this study is to model pathway relationships between Healthcare 4.0 enablers, contextual moderators, and UHC performance outcomes for NTDs in Nigeria. This objective reflects the need to examine Healthcare 4.0 not as isolated technological components, but as an integrated system operating within a broader socio-technical environment.

The specific objectives are to: (1) develop a socio-technical model specifying pathway linkages between Healthcare 4.0 technologies and UHC performance outcomes; (2) empirically estimate the pathways through which Healthcare 4.0 enablers influence effectiveness and efficiency of UHC for NTDs; (3) identify pathway-specific technological drivers associated with each performance dimension; (4) quantify the moderating effects of institutional readiness, policy and regulatory frameworks, socio-cultural acceptance, and economic capacity on these pathways; and (5) evaluate overall model fit and explanatory power using multivariate structural modeling techniques.

Materials and Methods

Research Paradigm and Design

The study was grounded in a positivist epistemological paradigm and followed a hypothetico-deductive approach within a quantitative design [14]. This orientation reflects the study's focus on testing predefined structural relationships among Healthcare 4.0 enablers, contextual moderators, and UHC performance outcomes. The choice of a quantitative framework was also shaped by the need for statistical precision, given the complexity of the constructs and the multivariate nature of the proposed model. The work forms part of a broader doctoral project in which the conceptual framework and structural pathways were developed and validated using LISREL-based analysis.

Study Setting and Population

The research was conducted in Nigeria, the most populous country in Africa, comprising 36 states and the Federal Capital Territory [17]. The study population consisted of three expert groups aligned with the conceptual model. Group A included UHC and NTD specialists in Nigeria (n = 111), such as clinicians, public health professionals, government officials, and development partners. Group B comprised Healthcare 4.0 and IT specialists in Nigeria (n = 100), including digital health practitioners and blockchain experts. Group C consisted of international Healthcare 4.0 experts (n = 103), who provided broader perspectives. This combination of local and international expertise was intended to balance contextual knowledge with comparative insights.

Sampling and Data Collection

A stratified purposive sampling strategy was used to ensure balanced representation across the three expert domains. Questionnaires were distributed to 375 eligible participants (125 per group), yielding 314 valid responses (response rate: 83.7%). The sample size exceeds recommended thresholds for Structural Equation Modeling (SEM), including minimum requirements for stable parameter estimation [15]. Data were collected using a structured questionnaire based on the conceptual framework, with items measured on a five-point Likert scale. A pilot test with 15 respondents was conducted to assess clarity and reliability, resulting in minor refinements to wording and structure. Ethical approval was obtained prior to data collection, and informed consent was secured from all participants. Participation was voluntary, and respondents

were assured that their identities would remain confidential.

Analytical Procedure

The analysis followed a structured multivariate sequence consisting of five stages, designed to progressively refine and validate the underlying model.

Stage 1: Descriptive Statistics: Means, standard deviations, skewness, and kurtosis were computed to assess data distribution and sample characteristics. Values within acceptable thresholds (±1 for skewness; ±2 for kurtosis) indicated approximate normality.

Stage 2: Principal Components Analysis (PCA): PCA with Varimax rotation and Kaiser normalization was used to identify underlying factor structures. Factor loadings ≥ 0.40 were retained. PCA served as a dimensionality-reduction step prior to confirmatory modeling, helping clarify how variables clustered empirically before imposing the theoretical structure.

Stage 3: Reliability Analysis: Cronbach's Alpha coefficients were computed to assess internal consistency. Values ≥ 0.70 were considered acceptable, while values ≥ 0.60 were deemed adequate for exploratory constructs [15].

Stage 4: Confirmatory Factor Analysis (CFA): CFA was conducted to validate the measurement model. Model fit was evaluated using χ^2/df, RMSEA, RMR, and SRMR. Convergent validity was assessed using standardized factor loadings (≥ 0.50) and Average Variance Extracted (AVE ≥ 0.50), while discriminant validity was assessed through inter-construct correlations.

Stage 5: Structural Equation Modeling (SEM): SEM was used to estimate structural path coefficients, T-values, and R^2 values, enabling explicit modeling of effectiveness and efficiency pathways and their interaction with contextual moderators. Both moderated and non-moderated models were estimated and compared. Model fit was evaluated using standard indices, including GFI, AGFI, NFI, NNFI, CFI, IFI, RFI, PNFI, and PGFI, with established thresholds applied (CFI/NNFI ≥ 0.90; RMSEA/SRMR ≤ 0.08) [15]. SEM was selected because it allows the simultaneous estimation of multiple relationships, which is essential for testing models. The use of multivariate structural modeling is consistent with methodological recommendations for analyzing complex socio-technical systems where multiple latent constructs interact simultaneously [25].

All analyses were conducted using SPSS for descriptive statistics, PCA, and reliability testing, and LISREL for CFA and SEM. Data screening and preparation were performed prior to analysis to ensure completeness and consistency.

Common Method Bias

To assess potential common-method bias, Harman's single-factor test was performed. The results showed that no single factor accounted for the majority of the variance, indicating that common-method bias was not a significant concern. While this does not eliminate all potential bias, it provides reasonable assurance that the findings were not dominated by measurement artifacts.

Results

Sample Profile

The final sample consisted of 314 respondents, with balanced representation across the three expert groups: Group A (35.4%), Group B (31.8%), and Group C (32.8%). Professional experience ranged from 5 to more than 20 years, and no respondent reported fewer than 5 years of domain experience. Knowledge of Healthcare 4.0 was distributed across scope (24.2%), architecture (28.0%), implementation (23.9%), and operations (23.9%), with a similar pattern observed for NTD-related knowledge.

Comparative analysis showed no statistically significant differences in response patterns across the three groups ($p > 0.05$), suggesting that perspectives were broadly consistent despite differences in professional background.

Descriptive Statistics

All 24 variables recorded mean scores clustered around 4.0 (High) on the five-point scale (range: 3.95–4.08). Standard deviations ranged from 0.733 to 0.802, indicating meaningful variability in expert perceptions. Skewness and kurtosis values fell within acceptable thresholds (±1 and ±2, respectively), confirming approximate normality. One-sample t-tests showed that all mean scores were significantly higher than the neutral midpoint (3.0) ($p < 0.001$), reflecting strong agreement among experts regarding the relevance of Healthcare 4.0 technologies within Nigeria's UHC context.

Reliability Analysis Results

Cronbach's Alpha values were 0.756 for Group 1 (NTD/UHC variables), 0.742 for Group 2 (Healthcare 4.0 variables), and 0.649 for the moderator group. Although the moderator value is lower, it remains acceptable for exploratory research [15]. No item deletion improved reliability, indicating that all items contributed meaningfully to their respective constructs.

PCA: Structural Differentiation of Effectiveness and Efficiency

PCA revealed a clear structural distinction between effectiveness and efficiency as two related but separate UHC performance dimensions. Governance-oriented variables, such as disease mapping, intervention monitoring, supply tracking, coverage expansion, institutional readiness, policy frameworks, and partnerships, loaded primarily onto the effectiveness factor. In contrast, data-intensive and computational variables, including big data, fog computing, fund utilization monitoring, insurance claims, socio-cultural acceptance, economic readiness, and blockchain, loaded onto the efficiency factor. This differentiation supports the idea that Healthcare 4.0 operates through multiple functional pathways rather than a single unified mechanism.

Model Comparison: Moderated vs. Non-moderated

The non-moderated model produced a p-value of 0.158 (confidence = 84.15%), while the moderated model yielded a p-value of 0.010 (confidence = 98.95%). This indicates that contextual moderators significantly improved model performance. Fit indices for the moderated model were strong: $\chi^2/df = 1.24$, RMSEA = 0.028, RMR = 0.025, SRMR = 0.043, NNFI = 0.99, CFI = 0.99, IFI = 0.99, NFI = 0.94, GFI = 0.93, and AGFI = 0.92. These results confirm that the moderated model provides a more accurate representation of the underlying relationships.

Structural Equation Modeling (SEM Results)

The structural relationships of the validated moderated model are presented in Figure 1.

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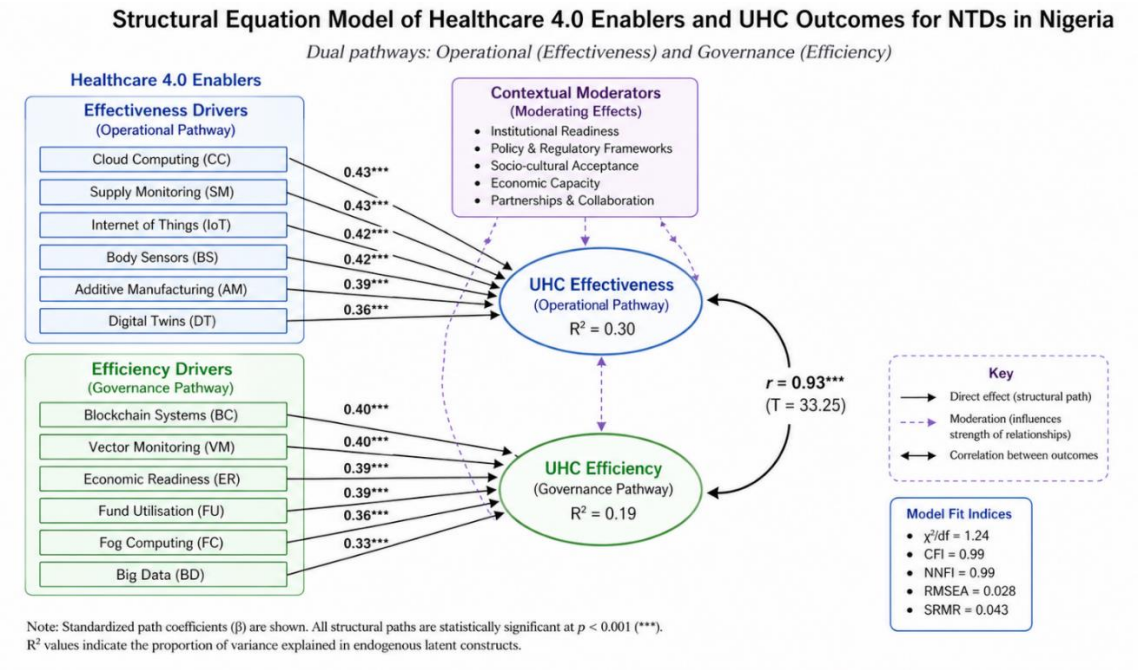

Figure 1. Structural Equation Model of Healthcare 4.0 and UHC Effectiveness and Efficiency for Neglected Tropical Diseases in Nigeria. Standardized path coefficients (β) are shown; all paths are statistically significant ($p < 0.001$)

Source: Authors' conceptualization and empirical results derived from the doctoral study

All hypothesized structural paths were statistically significant ($p < 0.001$). Technologies associated with continuous monitoring and data exchange, cloud computing ($\beta = 0.43$; $T = 9.87$), HIoT ($\beta = 0.42$; $T = 9.53$), and body sensors ($\beta = 0.42$; $T = 9.61$), showed the strongest positive effects on effectiveness. Governance-oriented and computational technologies demonstrated stronger effects on efficiency, with blockchain systems ($\beta = 0.40$; $T = 9.56$), vector monitoring ($\beta = 0.40$; $T = 8.88$), economic readiness ($\beta = 0.39$; $T = 9.11$), and fund utilization monitoring ($\beta = 0.39$; $T = 9.00$) emerging as the most influential predictors. These patterns reinforce the presence of two distinct but complementary pathways within the Healthcare 4.0–UHC relationship.

Contextual moderators, including institutional readiness, policy frameworks, socio-cultural acceptance, economic readiness, and partnerships, significantly strengthened the observed relationships, highlighting the importance of socio-technical alignment. The model explained a moderate proportion of variance in UHC performance ($R^2 = 0.19$–0.30), consistent with the complexity of health-system dynamics. A strong positive relationship was also observed between effectiveness and efficiency ($r = 0.93$; $T = 33.25$), indicating that improvements in one dimension tend to reinforce the other.

Integrated SEM Results

Table 1 summarizes the pathway-specific technological effects across both UHC performance dimensions. All variables exerted statistically significant effects ($p < 0.001$), with varying magnitudes across pathways. The consistency of these results across constructs and pathways provides robust empirical support for the proposed socio-technical model.

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Table 1. Comprehensive SEM Results: Integrated Socio-technical Framework Linking Healthcare 4.0 to UHC Effectiveness and Efficiency for NTDs in Nigeria

Variable	Outcome Dimension	β	T-value	R^2
Cloud Computing (HCC)	Effectiveness	0.43	9.87	0.30
Supply Monitoring (DSCMSUP)	Effectiveness	0.43	9.57	0.29
HIoT (HIOT)	Effectiveness	0.42	9.53	0.29
Body Sensors (HBS)	Effectiveness	0.42	9.61	0.29
Partnerships (PCP4NTDN)	Effectiveness	0.41	9.12	0.27
Additive Manufacturing (HAM)	Effectiveness	0.39	8.85	0.25
Coverage Expansion (DSCMNOE)	Effectiveness	0.38	8.58	0.24
Institutional Readiness (RHPINH4)	Effectiveness	0.37	8.60	0.24
Intervention Monitoring (DSCMIPC)	Effectiveness	0.37	8.64	0.24
Policy Frameworks (HPRFN)	Effectiveness	0.36	8.39	0.23
Digital Twins (HDT)	Effectiveness	0.36	8.23	0.22
Disease Mapping (DSCMMD)	Effectiveness	0.34	7.70	0.20
Blockchain Systems (HBC)	Efficiency	0.40	9.56	0.29
Vector Monitoring (DSCMVS)	Efficiency	0.40	8.88	0.26
Economic Readiness (ERH4NTDN)	Efficiency	0.39	9.11	0.27
Fund Utilization (DSCMUFC)	Efficiency	0.39	9.00	0.26
Fog Computing (HFC)	Efficiency	0.36	8.41	0.23
R&D Monitoring (DSCMRDI)	Efficiency	0.36	8.33	0.23
Socio-Cultural Acceptance (SCAH4NTDN)	Efficiency	0.36	8.10	0.22
Insurance Claims (DSCMIC)	Efficiency	0.36	8.10	0.22
Intervention Processes (DSCMIP)	Efficiency	0.34	8.07	0.22
Big Data (HBD)	Efficiency	0.33	7.53	0.19

Note: β = standardized path coefficient; T-values > 1.96 indicate statistical significance at 95% confidence level; all paths significant at $p < 0.001$

Discussion

The findings provide strong empirical support for an interpretation of Healthcare 4.0 within UHC systems. Rather than producing uniform effects, the results indicate that different technological components operate through distinct functional pathways, each aligned with specific performance dimensions. This distinction is particularly important for understanding how digital health interventions translate into outcomes.

Technologies that support continuous data exchange, ongoing monitoring, and enhanced clinical care, particularly cloud computing, IoT, and body sensors, show stronger associations with effectiveness. This indicates that improvements in effectiveness are primarily driven by enhanced system coordination, real-time visibility, and responsiveness in service delivery. This aligns with prior evidence showing that real-time digital ecosystems significantly improve clinical responsiveness and care coordination in health systems [23].

In contrast, efficiency is more strongly influenced by governance-oriented and computational infrastructures, including blockchain systems, financial monitoring mechanisms, and big data platforms. These technologies contribute to improved transparency, accountability, and resource optimization, all of which are central to efficiency gains in UHC systems, particularly

within broader health-system reform efforts aimed at strengthening UHC in LMICs [20]. Similar studies have demonstrated that blockchain-enabled governance and big-data infrastructures enhance transparency and resource optimization in LMIC health systems [24].

When considered together, this pattern reinforces the view of Healthcare 4.0 as an integrated system driver rather than a collection of standalone technological solutions. The results suggest that outcomes depend not only on technological capabilities but also on their alignment with institutional structures and operational processes. This is consistent with sociotechnical systems theory, which emphasizes that digital transformation outcomes depend on alignment between technological, organizational, and human components [25].

The significant moderating effects further demonstrate that the impact of Healthcare 4.0 is contingent on contextual readiness, consistent with implementation research perspectives that emphasize the role of contextual and institutional factors in health system interventions [21]. Institutional capacity, regulatory frameworks, socio-cultural acceptance, and economic conditions shape both the strength and direction of technological influence. This highlights the importance of coordinated, system-wide alignment in achieving sustainable digital health transformation. Recent digital health transformation frameworks similarly highlight that system-wide alignment is essential for achieving sustainable UHC improvements in resource-constrained settings [26, 29].

These findings are consistent with recent evidence from African NTD elimination programs, which identified institutional coordination, monitoring capacity, stakeholder collaboration, and sustainable system integration as critical determinants of program success [27]. The present study extends this evidence by demonstrating how Healthcare 4.0 technologies can operationalize these requirements through pathway-specific mechanisms that strengthen both effectiveness and efficiency within UHC systems.

A key implication is that policy and implementation strategies should prioritize coordinated system design rather than isolated technology adoption to achieve meaningful and sustained improvements in UHC performance, particularly as digital health becomes increasingly central to UHC in resource-constrained settings [22].

Contribution to Knowledge

This study advances the Healthcare 4.0 and UHC literature through four interrelated contributions.

First, it introduces an empirically validated dual-dimensional conceptualization of UHC performance (effectiveness and efficiency) for NTDs, thereby advancing the measurement of health-system outcomes beyond a single aggregated construct.

Second, it develops a context-sensitive socio-technical framework that links Healthcare 4.0 to UHC outcomes in LMIC settings, extending digital health theory to resource-constrained environments where constraints play a defining role.

Third, it provides an integrated multivariate validation of Healthcare 4.0–UHC relationships using Structural Equation Modeling, while empirically demonstrating the critical role of contextual moderators in shaping pathway-specific outcomes.

Fourth, it extends the NTD literature beyond predominantly clinical and intervention-focused perspectives by introducing a systems-level digital transformation paradigm for achieving UHC.

Limitations and Future Research

This study has several limitations that should be considered when interpreting the findings. The cross-sectional design restricts the ability to draw firm causal conclusions about how

Healthcare 4.0 adoption influences UHC performance over time. The relationships observed here should therefore be viewed as indicative patterns rather than definitive evidence of temporal change. Longitudinal data would be needed to capture how these pathways evolve as technologies mature and institutional conditions shift.

The reliance on expert perceptions also introduces potential response bias. Although the sample included experienced professionals across NTD, UHC, and digital health domains, their assessments may not fully reflect operational realities in frontline settings. This is particularly relevant in contexts where digital health systems are still emerging, and expectations about technology may outpace implementation capacity. Purposive sampling further limits generalizability beyond the expert groups included in the study.

The moderate explanatory power of the model ($R^2 = 0.19–0.30$) reflects the complexity of health system performance, which is shaped by numerous structural, political, and contextual factors not captured by the current framework. Variables such as governance quality, policy enforcement, interoperability constraints, and informal system dynamics likely play important roles but were beyond the scope of this analysis.

Future research should incorporate longitudinal designs, mixed-methods approaches, and broader institutional variables to deepen understanding of how Healthcare 4.0 interacts with UHC systems in practice.

Conclusion

This study provides empirical evidence on how Healthcare 4.0 technologies influence the effectiveness and efficiency of Universal Health Coverage (UHC) for Neglected Tropical Diseases (NTDs) in Nigeria. The results indicate that digital technologies do not operate in isolation; rather, their effects emerge through distinct but interrelated pathways shaped by contextual conditions. Technologies that support continuous data exchange and real-time monitoring are more strongly associated with effectiveness, while governance-oriented and computational infrastructures, such as blockchain systems and big data analytics, are more closely linked to efficiency.

These results highlight the importance of conceptualizing digital transformation as a process rather than a collection of discrete technological interventions. The strength and direction of these relationships are significantly influenced by contextual moderators, including institutional readiness, policy frameworks, socio-cultural acceptance, and economic capacity. The results highlight the need for alignment between technological capabilities and the broader institutional environment.

In settings such as Nigeria, where digital health initiatives often operate in fragmented silos, such alignment becomes essential for achieving meaningful and sustained improvements in UHC performance. The study contributes a validated socio-technical model that can inform policymakers, implementers, and development partners in designing more integrated and context-responsive digital health strategies for NTD control. The findings also support recent calls for integrated, technology-enabled approaches to NTD elimination in Africa that combine digital innovation with strong institutional and governance structures [27].

While the model explains a moderate proportion of variance, it provides a structured foundation for understanding how Healthcare 4.0 can support UHC goals in resource-constrained contexts. Overall, the findings suggest that digital technologies, when embedded within supportive governance and institutional systems, can play a central, enabling role in strengthening health-system performance and advancing progress toward UHC [29]. This reinforces the need to move beyond technology adoption toward digital integration in UHC policy design.

Conflict of Interest

The authors declare no conflict of interest. This study was conducted as part of doctoral research at Texila American University, without financial or institutional bias.

Ethical Approval

Ethical clearance was obtained from the Texila American University Institutional Review Board (IRB/TAU/2024/H4UHC/004), in compliance with the Declaration of Helsinki (2013). Informed consent was obtained from all 314 participants. Anonymity and data confidentiality were maintained throughout.

Data Availability

Anonymized study-level data are available from the corresponding author upon reasonable request, subject to institutional approval. The theoretical framework and LISREL output are available as supplementary material.

Author Contributions

- **YYI:** Conceptualization; theoretical framework development; data collection; formal analysis (PCA, CFA, SEM); writing original draft; review, and editing.
- **AOP**: Methodology supervision; critical appraisal of the analytical approach and findings; writing, review, and editing.
- **ALR**: Conceptual refinement; validation of analytical framework; critical review and editing of manuscript.

All authors have read and approved the final manuscript.

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