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Blockchain-Enabled Smart Contract Monitoring and Universal Health Coverage Efficiency for Neglected Tropical Diseases in Nigeria

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Abstract *This study examines the role of blockchain-enabled monitoring systems in enhancing the efficiency of Universal Health Coverage (UHC) for Neglected Tropical Diseases (NTDs) in Nigeria. Despite ongoing policy efforts, UHC delivery remains constrained by fragmented governance structures, weak financial transparency, and limited real-time performance monitoring. Blockchain technology, operationalized through smart contract–based mechanisms, offers a pathway to strengthen accountability, improve resource tracking, and optimize system efficiency. A quantitative cross-sectional design was employed using data from 314 health system stakeholders across three expert groups: UHC and NTD specialists, Healthcare 4.0 and IT experts, and international digital health professionals. Data were analyzed using Principal Components Analysis (PCA), reliability testing, Confirmatory Factor Analysis (CFA), and Structural Equation Modeling (SEM). The model demonstrated strong fit (RMSEA = 0.028; SRMR = 0.043; CFI = 0.99). Findings show that blockchain-enabled monitoring systems significantly influence UHC efficiency, with Blockchain systems (HBC) (β = 0.40) and fund utilization monitoring (β = 0.39) as the strongest drivers. Big data (β = 0.33), fog computing (β = 0.36), socio-cultural acceptance (β = 0.36), and economic readiness (β = 0.39) also showed significant effects. Efficiency gains are driven by integrated monitoring architectures that align governance mechanisms, data infrastructure, and contextual readiness conditions. These findings provide policy-relevant evidence for strengthening transparent and efficient UHC systems for NTD control in resource-constrained settings.*

Keywords *Blockchain, Health System Efficiency, Neglected Tropical Diseases, Nigeria, Smart Contracts, Universal Health Coverage.*

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Introduction

Nigeria's Universal Health Coverage (UHC) system faces profound efficiency challenges. With fewer than 5% of the population enrolled in the National Health Insurance Scheme, over 70% of healthcare expenditure financed out of pocket, and limited integration of performance monitoring systems, the UHC framework for Neglected Tropical Diseases (NTDs) remains largely reactive and fragmented [1, 2, 9, 17]. Efficiency, encompassing resource optimization, cost control, and system responsiveness, is critical for achieving sustainable NTD elimination within constrained financial and human resource environments. These challenges reflect not only resource limitations but also systemic inefficiencies in governance structures, data visibility, and real-time performance monitoring within the health system [1, 2]. In practice, these inefficiencies reinforce one another, constraining overall system responsiveness and performance.

Blockchain-enabled monitoring systems, a foundational component of Healthcare 4.0, provide a distributed, immutable infrastructure for transparent, secure, and real-time tracking of healthcare transactions, supply chains, funding flows, and intervention performance [3–5, 15, 18]. Through smart contracts, governments and health institutions can automate monitoring processes, reduce leakages, and enhance accountability without reliance on centralized administrative controls [5]. Within this context, blockchain-enabled monitoring systems function as governance mechanisms that restructure coordination, traceability, and oversight across health system operations.

Nigeria's National Information Technology Development Agency (NITDA) identifies blockchain as a key enabler of digital transformation in healthcare, particularly for managing health data and strengthening institutional accountability [6]. This policy alignment provides a relevant basis for examining blockchain-enabled governance within UHC delivery for NTDs in a resource-constrained setting, supported by global digital health strategies [16].

Despite its relevance, the relationship between blockchain-enabled monitoring systems and UHC efficiency for NTDs in Nigeria remains underexplored. Existing studies largely focus on conceptual discussions or high-income contexts, limiting their applicability to Nigeria's institutional and infrastructural realities [3–5, 7, 19]. Furthermore, limited attention has been given to how blockchain systems interact with complementary Healthcare 4.0 technologies and contextual factors influencing implementation. This results points to the need for an integrated analytical perspective that captures the joint influence of governance mechanisms, computational infrastructure, and contextual readiness on efficiency outcomes.

Drawing on Healthcare 4.0 and digital health governance literature [3–7, 16], this study adopts a socio-technical framework in which blockchain-enabled monitoring systems interact with complementary computational technologies (e.g., big data analytics and fog computing) and contextual factors (e.g., socio-cultural acceptance and economic readiness) to influence UHC efficiency outcomes. Within this framework, efficiency is conceptualized as a governance-driven performance dimension shaped by transparency, accountability, and data-enabled coordination.

This study addresses these gaps by employing a quantitative structural equation modeling approach to identify and validate the monitoring mechanisms most strongly associated with efficiency outcomes. The findings contribute to understanding how blockchain-enabled monitoring systems can strengthen transparency, accountability, and coordination within UHC delivery for NTDs in Nigeria. This manuscript is derived from a broader doctoral study that developed and validated an integrated socio-technical

framework linking Healthcare 4.0 to UHC performance outcomes in Nigeria. This study represents a focused sub-analysis of a broader structural model, isolating the efficiency pathway to provide a more granular examination of governance-driven performance mechanisms. By doing so, it provides empirical evidence on how integrated digital health systems translate into measurable efficiency gains in resource-constrained settings.

Research Objectives

Specific objectives were to: (1) identify variables loading significantly onto UHC efficiency through Principal Components Analysis; (2) to validate the measurement model through Confirmatory Factor Analysis; (3) estimate structural path coefficients using Structural Equation Modeling (SEM); and (4) discuss the implications of the findings for Nigeria's health system digitalization strategy.

These objectives operationalize the empirical testing of governance, computational, and contextual determinants of efficiency within a unified analytical framework [8].

Materials and Methods

Design and Sample

A quantitative cross-sectional survey design was employed. Data were collected from 314 health system stakeholders across three expert groups: Group A: UHC and NTD specialists in Nigeria (n = 111); Group B: Healthcare 4.0 and IT specialists in Nigeria (n = 100); and Group C: international Healthcare 4.0 experts (n = 103). Stratified purposive sampling ensured balanced domain representation. The sample size exceeds the recommended minimum of 200–250 observations for SEM stability [8].

This study is derived from a broader doctoral research project in which the conceptual framework and structural relationships were developed and validated using LISREL-based multivariate analysis. This sub-analysis specifically focuses on the efficiency pathway within the broader socio-technical framework, examining governance, computational, and contextual determinants of UHC performance.

Measurement Instrument

A structured questionnaire measured each variable on a five-point interval scale (1 = Very Low to 5 = Very High). Variables in the efficiency domain included 10 blockchain-based smart contract monitoring items, 9 general Healthcare 4.0 technology items, and 5 contextual moderator items, consistent with the initial theoretical framework. The instrument was validated through a 15-respondent pilot study prior to full deployment. The pilot phase enabled assessment of item clarity, internal consistency, and construct alignment, and informed minor refinements in wording and structure to enhance measurement accuracy and respondent understanding.

Analytical Approach

Data were analyzed using SPSS and LISREL. Descriptive statistics confirmed data normality (all skewness values $< \pm 0.14$; all kurtosis values within ± 2). PCA with Varimax rotation identified variables loading significantly (≥ 0.40) onto efficiency. Cronbach's Alpha assessed internal consistency. CFA validated measurement model fit, and SEM estimated structural path coefficients. Model fit was evaluated using established thresholds: CFI and NNFI ≥ 0.90 indicate acceptable fit, while RMSEA and SRMR ≤ 0.08 indicate reasonable approximation error [8].

This sequential analytical procedure reflects a multivariate modeling strategy in which exploratory (PCA), confirmatory (CFA), and structural (SEM) stages are integrated to ensure robustness and validity of the estimated relationships.

The analytical framework is grounded in a socio-technical perspective, where blockchain-enabled monitoring systems, complementary computational technologies (e.g., big data analytics and fog computing), and contextual

readiness factors (e.g., socio-cultural acceptance and economic readiness) jointly influence UHC efficiency outcomes.

Results

Reliability and Data Quality

Cronbach's Alpha coefficients were 0.756 (Group 1: NTD/UHC-specific variables) and 0.742 (Group 2: general Healthcare 4.0 variables), both within acceptable ranges. The moderator group yielded $\alpha = 0.649$, which is acceptable for exploratory research [8]. These reliability values indicate satisfactory internal consistency of the measurement scales, supporting their suitability for multivariate analysis [8]. Descriptive statistics confirmed near-normal distributions for all variables, with means clustered around 4.0 (High) and standard deviations between 0.73 and 0.81. Skewness and kurtosis values remained within acceptable thresholds, further supporting the assumption of normality required for SEM estimation [8].

One-sample t-tests further confirmed that mean scores for all variables were significantly higher than the neutral midpoint (3.0) ($p < 0.001$), indicating consistently positive expert perceptions regarding the relevance and applicability of blockchain-enabled Healthcare 4.0 technologies within the Nigerian UHC context.

PCA: Variables Loading onto Efficiency

Varimax-rotated PCA identified the following variables loading significantly (≥ 0.40) onto UHC efficiency: Monitoring of vectors and NTD spread (DSCMVS = 0.572); Monitoring of research and development innovations (DSCMRDI = 0.726); Monitoring of intervention processes (DSCMIP = 0.548); Monitoring of UHC fund utilization (DSCMUFC = 0.507); Monitoring of insurance claims (DSCMIC = 0.598); Healthcare big data (HBD = 0.695); Healthcare blockchains (HBC = 0.465); Fog computing (HFC = 0.753); Socio-cultural acceptance (SCAH4NTDN = 0.869); Economic readiness (ERH4NTDN = 0.656). All retained variables exceeded the minimum loading threshold of 0.40, indicating strong contributions to the latent efficiency construct [8]. These loadings confirm the structural differentiation between efficiency and effectiveness, with computational, financial governance, and social readiness variables predominantly associated with efficiency. This pattern supports the theoretical expectation that efficiency outcomes are primarily driven by governance, monitoring, and computational infrastructure variables rather than by clinical or service-delivery technologies. These results further indicate that efficiency is structurally linked to accountability-driven and data-intensive system functions within the Healthcare 4.0 framework.

SEM Results: Blockchain Monitoring and Efficiency

The structural relationships of the validated model are presented in Figure 1. The model demonstrated satisfactory goodness-of-fit, consistent with established SEM thresholds ($RMSEA \leq 0.08$; $SRMR \leq 0.08$; $CFI \geq 0.90$), indicating that the hypothesized structure adequately represents the observed data [8]. This structure reflects the underlying socio-technical framework guiding the analysis.

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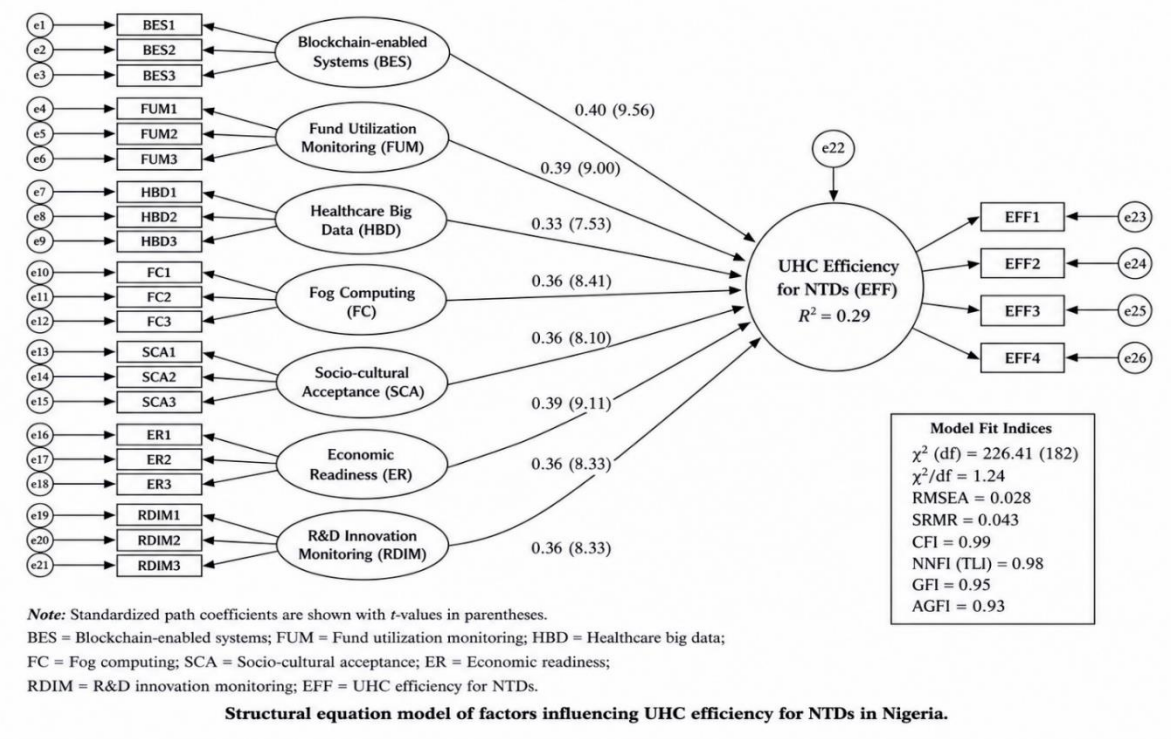

Figure 1. Structural Equation Model of Factors Influencing UHC Efficiency for NTDs in Nigeria

Source: Author's conceptualization and empirical results derived from the doctoral study.

Table 1. Structural Equation Modeling Results: Determinants of UHC Efficiency for NTDs in Nigeria

Variable	B	R^2	T-value	Key Interpretation
Blockchain Systems (HBC)	0.40	0.29	9.56	Primary governance layer; secure data integration
Fund Utilization Monitoring (DSCMUFC)	0.39	0.26	9.00	Transparency in NTD fund allocation and expenditure
Economic Readiness (ERH4NTDN)	0.39	0.27	9.11	Financial capacity moderates technology efficiency
NTD Vector Monitoring (DSCMVS)	0.40	0.26	8.88	Blockchain-enabled vector surveillance
Fog Computing (HFC)	0.36	0.23	8.41	Local real-time analytics at care centers
R&D Innovation Monitoring (DSCMRDI)	0.36	0.23	8.33	Smart contracts for clinical trials and drug development
Insurance Claims Monitoring (DSCMIC)	0.36	0.22	8.10	Blockchain monitoring of NHIS claims processing
Socio-Cultural Acceptance (SCAH4NTDN)	0.36	0.22	8.10	User acceptance reduces adoption friction
Intervention Processes (DSCMIP)	0.34	0.22	8.07	Government-directed accountability monitoring
Healthcare Big Data (HBD)	0.33	0.19	7.53	Infrastructure for advanced analytics and AI

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

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

Detailed structural path coefficients and explanatory power of each determinant are presented in Table 1. All structural paths were statistically significant (T-values > 1.96), indicating strong empirical support for the hypothesized relationships [8]. Blockchain-enabled monitoring systems (HBC) (β = 0.40) and NTD vector monitoring (β = 0.40) emerged as the strongest predictors of efficiency, closely followed by fund utilization monitoring (β = 0.39) and economic readiness (β = 0.39). These findings highlight the central role of governance, financial transparency, and contextual readiness in driving efficiency within UHC systems. The magnitude and consistency of these coefficients suggest that governance-oriented technologies exert a more pronounced influence on efficiency outcomes than purely technical or clinical innovations. The reported R^2 values (0.19–0.29) indicate moderate explanatory power, consistent with the multifactorial nature of health system efficiency and suggesting that additional contextual and institutional factors may also contribute to observed outcomes [8]. This level of explanatory power is consistent with expectations in complex socio-technical systems, where multiple interacting determinants shape performance outcomes.

Correlation Between Effectiveness and Efficiency

The correlation between effectiveness and efficiency was strong (r = 0.93, T = 33.25), indicating that improvements in efficiency are closely associated with gains in effectiveness. This strong relationship suggests that while efficiency and effectiveness are conceptually distinct constructs, they are empirically interdependent within the UHC framework, reinforcing the integrated nature of health system performance outcomes. This interdependence highlights the importance of coordinated system-level interventions that simultaneously address both performance dimensions.

Discussion

The findings of this study provide robust empirical evidence on the role of blockchain-enabled monitoring systems in improving the efficiency of UHC for NTDs in Nigeria. Blockchain-enabled monitoring systems (β = 0.40) and fund utilization monitoring (β = 0.39) emerged as the strongest predictors, underscoring the central importance of institutional control structures in shaping health system performance. These results suggest that inefficiencies within Nigeria's UHC system are driven not only by resource constraints but also by limitations in oversight, coordination, and financial transparency across system functions [3–5].

Consistent with the descriptive results, the uniformly high mean scores and significant t-test outcomes ($p < 0.001$) suggest strong expert consensus on the relevance of blockchain-enabled Healthcare 4.0 technologies. This indicates that their perceived importance reflects a shared recognition of their potential within the Nigerian health system context.

From a theoretical perspective, the findings support the positioning of blockchain not merely as a technological innovation but as an institutional infrastructure embedded within Healthcare 4.0 systems. This aligns with digital health governance literature, which emphasizes integrating technological capabilities with organizational and regulatory processes to enable system-level transformation [3, 4, 16, 19]. In this study, blockchain-enabled smart contracts function as automated monitoring mechanisms that reduce information asymmetry, minimize resource leakages, and strengthen accountability across fund flows and intervention processes [15, 18]. Their application in healthcare supply chains has also been shown to enhance traceability and improve transparency in resource-limited settings [10].

The PCA results reinforce this interpretation by demonstrating that efficiency is structurally associated with governance-oriented,

computational, and socio-contextual variables. Variables such as fog computing, big data analytics, and socio-cultural acceptance exhibited strong loadings, indicating that efficiency outcomes are shaped by data-intensive and accountability-driven system functions rather than by clinical service delivery components.

The strong contribution of fund utilization monitoring ($\beta = 0.39$) highlights the importance of financial traceability in improving efficiency. In contexts characterized by high out-of-pocket expenditure and limited insurance coverage, inefficiencies are often linked to weak financial oversight and delayed accountability mechanisms [11, 12]. Blockchain-enabled monitoring systems address this gap by enabling verifiable and traceable transactions, thereby reducing inefficiencies associated with misallocation, delays, and information asymmetry. However, their effectiveness remains contingent on institutional adoption, regulatory enforcement, and interoperability with existing health information systems.

Complementary computational technologies further reinforce the socio-technical nature of efficiency outcomes. Fog computing ($\beta = 0.36$) and healthcare big data ($\beta = 0.33$) contribute by enabling decentralized data processing and advanced analytics, supporting continuous data exchange and localized decision-making for NTD interventions in underserved populations [13].

Socio-cultural acceptance ($\beta = 0.36$) and economic readiness ($\beta = 0.39$) emerged as significant moderating factors, confirming that the effectiveness of blockchain-enabled monitoring systems is conditioned by contextual realities. This finding aligns with socio-technical and technology adoption theories, which emphasize that outcomes are shaped by interactions between technical systems and social environments [7, 20]. Broader digital health adoption challenges in Nigeria—including infrastructural gaps, limited system readiness, and uneven digital literacy—have been widely documented and remain critical considerations for implementation [14].

The SEM results provide strong evidence that governance-oriented technologies exert the most substantial influence on efficiency outcomes, as reflected in the magnitude and consistency of the standardized path coefficients. This indicates that improvements are primarily driven by enhanced transparency, coordination, and accountability mechanisms rather than by isolated technological enhancements.

Although all structural paths were statistically significant, the model's moderate explanatory power ($R^2 = 0.19–0.29$) reflects the inherent complexity of health system performance. Efficiency outcomes are influenced by multiple interacting factors, including governance quality, regulatory enforcement, and institutional capacity, which extend beyond the variables captured in the present model.

The strong correlation between effectiveness and efficiency ($r = 0.93$) underscores the interdependence of UHC performance dimensions. While analytically distinct, improvements in efficiency appear to reinforce effectiveness, suggesting that system-level interventions should address both dimensions simultaneously.

From a policy perspective, the findings indicate that improving UHC efficiency for NTDs in Nigeria requires a shift from fragmented monitoring approaches to integrated, blockchain-enabled governance architectures. However, large-scale implementation is likely to face practical constraints, including infrastructure limitations, interoperability challenges, regulatory uncertainty, and shortages of skilled human resources. Initial deployment costs may also present barriers in resource-constrained settings, consistent with broader evidence on digital health implementation in LMICs [19].

Overall, this study advances the literature by demonstrating that improvements in UHC efficiency are driven by the interaction of governance mechanisms, computational infrastructure, and contextual readiness. It contributes to a more nuanced understanding of Healthcare 4.0 by positioning blockchain-enabled monitoring systems as embedded governance infrastructures within broader socio-technical systems. Taken together, the findings indicate that meaningful efficiency gains depend on coordinated alignment between technology, institutions, and context rather than on technological adoption alone.

Limitations

The cross-sectional design limits the ability to establish causal relationships regarding the temporal dynamics of blockchain adoption and UHC efficiency improvements. As a result, the observed associations should be interpreted as indicative rather than definitive evidence of causality.

In addition, reliance on expert responses, particularly among Group B participants in contexts where blockchain-enabled healthcare systems are still in early stages of implementation, may introduce perception bias. The use of self-reported data may also be subject to response bias, potentially influencing the accuracy of reported relationships. This may affect the generalizability of findings to fully operational health system environments where blockchain applications are more mature.

The moderate R^2 values (0.19–0.29) reflect the inherent complexity of efficiency as a multifactorial health system outcome rather than model inadequacy. These values are consistent with expectations for socio-technical systems in which multiple interacting institutional, technological, and contextual factors influence performance outcomes.

Furthermore, the study does not fully capture broader institutional and regulatory dimensions, such as governance quality, policy enforcement, and interoperability constraints, which may also influence the effectiveness of blockchain-enabled monitoring systems.

Future research should employ longitudinal designs and incorporate objective administrative data to enable stronger causal inference and validate the observed relationships over time. Comparative multi-country studies across low- and middle-income countries (LMICs) would enhance external validity, while mixed-methods approaches could provide deeper insights into implementation dynamics, governance processes, and contextual adaptation. Additional research should also incorporate institutional and policy variables to enhance the model's explanatory power and provide a more comprehensive understanding of efficiency dynamics within UHC systems.

Conclusion

The findings of this study provide empirically grounded evidence on the relationship between blockchain-enabled monitoring systems and the efficiency of UHC for NTDs in Nigeria. Blockchain systems (HBC), fund utilization monitoring, economic readiness, and vector surveillance emerged as the strongest predictors, while fog computing, big data analytics, socio-cultural acceptance, and R&D innovation monitoring provided important complementary contributions.

The results indicate that improving UHC performance for NTDs requires a coordinated strategy that integrates blockchain-based governance mechanisms with advanced data infrastructures, sustainable financing structures, and community-level acceptance. These findings suggest that efficiency gains depend on the alignment of governance mechanisms, computational capabilities, and contextual readiness conditions, rather than on isolated technological adoption.

This study provides an empirically validated, context-specific model of Healthcare 4.0 implementation in a low- and middle-income country setting, demonstrating how blockchain-

enabled governance can enhance performance within UHC systems. It advances a socio-technical perspective in which improvements are achieved through the interaction of institutional control structures, computational technologies, and contextual readiness, consistent with established theoretical frameworks on technology adoption and system integration [7, 20].

Overall, the study contributes a pathway-based understanding of digital health transformation, showing that meaningful efficiency improvements are driven by coordinated interactions between technology, institutions, and context within complex health systems.

Conflict of Interest

The authors declare no conflict of interest. This study was conducted independently as part of doctoral research at Texila American University.

Ethical Approval

Ethical clearance was obtained from the Texila American University Institutional Review Board (IRB/TAU/2024/H4UHC/002). Informed consent was obtained from all participants. Participant 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.

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.
- A**LR**: 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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