Jurnal Kejuruteraan 38(7) 2026: 3287-3301
https://doi.org/10.17576/jkukm-2026-38(7)-10

A Secure and Patient-Centric Digital Twin–Blockchain Framework for Type 2 Diabetes Management

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Received 16 January 2026, Received in revised form 3 July 2026
Accepted 3 August 2026, Available online 30 October 2026

ABSTRACT

The management of Type 2 Diabetes Mellitus (T2DM) is increasingly challenged by fragmented healthcare information systems, reactive care models, limited interoperability, and growing concerns regarding data privacy, security, and governance. Previous research established and validated a collaborative knowledge management model for T2DM self-management, demonstrating the importance of monitoring parameters, knowledge quality, and stakeholder collaboration in supporting effective disease management. Building upon this foundation, this study proposes a conceptual Digital Twin (DT) and blockchain-enabled framework to support secure, personalized, and knowledge-driven T2DM management. Using a design-oriented approach, the framework integrates contemporary digital health technologies with established self-management principles to address both personalization and trust-related challenges. The proposed architecture comprises four interconnected layers: (i) data acquisition and integration, (ii) DT modelling and adaptive patient representation, (iii) blockchain-enabled governance, and (iv) clinical decision support. The framework incorporates standards-based interoperability through HL7 FHIR, near-real-time synchronization of patient data, adaptive DT updating mechanisms, and permissioned blockchain smart contracts for consent management, access control, auditability, and data integrity. The DT layer supports patient-specific monitoring and predictive "what-if" simulations, while the blockchain layer provides transparent and accountable governance of health information exchanges. Rather than presenting a clinical implementation, this work provides a theoretically grounded reference architecture that operationalizes a previously validated diabetes self-management model using DT and blockchain technologies. The proposed framework offers a foundation for future prototype development, simulation studies, and pilot clinical evaluations aimed at assessing clinical effectiveness, user acceptance, trust, and governance performance in secure DT-enabled chronic disease management environments.

Keyword: Diabetes management; digital twins; blockchain; trust; smart contracts

INTRODUCTION

Type 2 Diabetes Mellitus (T2DM) is a major global public health challenge, with prevalence continuing to rise due to ageing populations, sedentary lifestyles, and changing dietary patterns (International Diabetes Federation 2023; Lu et al. 2024). As a chronic metabolic disorder characterised by insulin resistance and impaired glucose regulation, T2DM is associated with severe long-term complications, including cardiovascular disease, nephropathy, neuropathy, and retinopathy (Ahmad et al. 2022). Despite advances in pharmacological therapies and clinical guidelines, effective long-term management of T2DM remains difficult, as care is often reactive, fragmented, and insufficiently personalised to individual patient needs (Daly & Hovorka 2021; Conlin et al. 2024).

Recent years have seen growing interest in digital health technologies aimed at improving chronic disease management through continuous monitoring, predictive analytics, and patient engagement. Among these, Digital Twins (DTs) have emerged as a promising paradigm for personalised healthcare. By creating a dynamic virtual representation of a patient that is continuously updated

with real-world clinical and behavioural data, DTs enable real-time monitoring, risk prediction, and simulation of treatment scenarios without exposing patients to unnecessary harm (Vallée 2023; Zhang et al. 2024). In the context of T2DM, DTs have been explored for glucose dynamics modelling, therapy optimisation, and personalised lifestyle intervention planning, demonstrating potential to shift care from reactive management toward proactive and predictive decision-making (Karamanos et al. 2025; Zhang et al. 2024).

However, the effectiveness of DTs-driven healthcare systems is fundamentally dependent on the availability, integrity, and secure governance of large volumes of sensitive patient data. Continuous data streams from wearable sensors, continuous glucose monitors, and electronic health records introduce significant privacy, security, and trust challenges, particularly when data are shared across multiple stakeholders and organisational boundaries (Jørgensen et al. 2023; Okegbile et al. 2023). Without robust mechanisms for access control, consent management, and auditability, the deployment of DTs in real-world clinical environments risks undermining patient trust and regulatory compliance.

Blockchain technology has been widely proposed as a complementary solution to these challenges due to its decentralised architecture, cryptographic security, and immutable ledger properties (Chen et al. 2018; Yaqoob et al. 2021). In healthcare contexts, blockchain has been applied to secure medical records, enforce patient-centric access control, and enable transparent audit trails for data sharing and governance (Huang et al. 2020; Tanwar et al. 2020). Permissioned blockchain models, in particular, offer controlled participation and efficient consensus mechanisms suitable for clinical environments, supporting compliance with data protection regulations such as GDPR and HIPAA (Yaqoob et al. 2021; Gupta et al. 2024).

While prior studies have investigated DTs and blockchain technologies independently within healthcare, existing approaches often address personalisation and data governance in isolation. DTs–centric solutions tend to focus on predictive modelling and decision support, frequently assuming the existence of secure and interoperable data infrastructures (Meijer et al. 2023; Katsoulakis et al. 2024). Conversely, blockchain-based healthcare frameworks emphasise data security, access control, and auditability, but offer limited integration with patient-specific modelling and clinical decision-making processes (Amofa et al. 2024; Gahlawat & Tanwar 2025). As a result, few solutions provide a coherent, end-to-end architecture capable of supporting both personalised care and trustworthy data governance for long-term T2DM management.

This study addresses this gap by proposing a conceptual, end-to-end framework that integrates patient-specific DTs with a permissioned blockchain infrastructure for secure and personalised T2DM management. The framework combines continuous data acquisition, predictive DTs modelling, blockchain-based consent and access governance, and standards-based interoperability to enable transparent, patient-centric decision support. By explicitly aligning personalisation with security, privacy, and trust mechanisms, the proposed architecture provides a scalable foundation for future clinical validation and real-world deployment of DTs–enabled chronic disease management systems.

BACKGROUND AND RELATED WORK

CURRENT CHALLENGES IN TYPE II DIABETES MELLITUS MANAGEMENT

The management of T2DM requires continuous monitoring, long-term behavioural adaptation, and coordinated clinical decision-making. Although contemporary clinical guidelines promote individualized glycaemic targets and multidisciplinary care, real-world management remains constrained by fragmented data systems, delayed intervention, and limited integration of patient-generated health data into routine clinical workflows (Daly & Hovorka 2021; Conlin et al. 2024). Continuous glucose monitoring, wearable devices, and telemedicine platforms offer substantial potential to enhance patient engagement and glycaemic control; however, their impact in T2DM has been inconsistent due to interoperability barriers, data silos, and insufficient real-time decision support (Ahmad et al. 2022; Liakos et al. 2023, Ramlana, L. A. 2025).

A critical limitation of current T2DM care lies in the lack of truly personalised, predictive models capable of integrating heterogeneous clinical, behavioural, and physiological data over long-time horizons. Most care pathways remain protocol-driven rather than adaptive, limiting the ability to anticipate disease progression or simulate the effects of alternative interventions (Lu et al. 2024; Maina et al. 2023). These challenges motivate the exploration of advanced digital paradigms capable of supporting personalised, proactive, and data-driven T2DM management.

DIGITAL TWINS IN HEALTHCARE

DTs have emerged as a promising approach for personalised healthcare by enabling dynamic virtual representations of patients that evolve alongside real-world data streams (Vallée 2023; Katsoulakis et al. 2024). In healthcare contexts, DTs are typically synchronised with physiological

sensors, electronic health records, and behavioural data to support monitoring, prediction, and simulation of treatment strategies (Laubenbacher et al. 2024). Applications of DTs have been reported across chronic disease management, including diabetes, cardiovascular conditions, and neurological disorders, demonstrating their potential for patient-specific modelling and predictive decision support (Karamanos et al. 2025; Zhang et al. 2024).

Despite their promise, DTs-based healthcare systems face significant challenges related to data quality, model validation, interoperability, and long-term reliability (Meijer et al. 2023; Okegbile et al. 2023). More critically, DTs rely on continuous access to sensitive patient data across distributed systems, raising concerns regarding privacy, security, and trust. Without robust governance mechanisms, the clinical deployment of DTs risks undermining patient confidence and regulatory compliance, particularly in multi-stakeholder healthcare ecosystems (Jørgensen et al. 2023).

BLOCKCHAIN FOR HEALTHCARE DATA GOVERNANCE

Blockchain technology has been widely investigated as an enabling infrastructure for secure and transparent healthcare data management. Its decentralised architecture, cryptographic security, and immutable ledger properties make it well suited for enforcing access control, consent management, and auditability in distributed health information systems (Chen et al. 2018; Yaqoob et al. 2021). In healthcare applications, permissioned blockchain models are often preferred due to their controlled participation, efficient consensus mechanisms, and compatibility with regulatory requirements (Tanwar et al. 2020; Gupta et al. 2024).

Blockchain-based solutions have been proposed for electronic health record sharing, patient-centric consent governance, and secure medical data exchange across institutional boundaries (Huang et al. 2020; Amofa et al. 2024). However, while blockchain excels at data governance and trust management, it does not inherently provide clinical intelligence or personalised decision support. As such, blockchain-only approaches offer limited value for chronic disease management unless tightly integrated with advanced analytical models capable of interpreting patient data in a clinically meaningful way (Gahlawat & Tanwar 2025).

EXISTING ATTEMPTS AT INTEGRATING DIGITAL TWINS AND BLOCKCHAIN

Recent studies have begun exploring the integration of DTs and blockchain technologies to address both personalisation and data governance in healthcare. Prior work has demonstrated the feasibility of patient-centric DTs models combined with blockchain-based access control and secure data sharing (Amofa et al. 2024; Gahlawat & Tanwar 2025). In the T2DM domain, DT-driven approaches have shown promise for glucose prediction and treatment optimisation, while blockchain mechanisms have been used to enhance data security and consent management (Karamanos et al. 2025; Tandon et al. 2025).

Nevertheless, existing integration efforts exhibit notable limitations. Many studies treat DTs and blockchain as loosely coupled components, with limited consideration of their coordinated operation within end-to-end clinical workflows (Zhang et al. 2024). Interoperability standards, formal consent traceability, and transparent decision-support integration are often underdeveloped or absent. Furthermore, most reported systems remain at the conceptual or proof-of-concept stage, with limited discussion of scalability, clinical integration, and long-term sustainability (Okegbile et al. 2023; Meijer et al. 2023). Table 1 presents a comparative summary of representative studies relevant to healthcare and T2DM management to systematically contrast existing DTs and blockchain-based healthcare approaches and to highlight persistent gaps in personalisation, data governance, interoperability, and evaluation maturity.

THEORETICAL FOUNDATIONS AND CONCEPTUAL FRAMEWORK TRANSITION

THEORETICAL FOUNDATIONS

The proposed framework is grounded in established theories of patient-centric care, socio-technical systems, and trusted digital infrastructures, which collectively inform the integration of DTs and blockchain technologies for chronic disease management. Patient-centric care theory emphasises the active involvement of individuals in managing their health through personalised interventions, continuous feedback, and shared decision-making between patients and clinicians (Daly & Hovorka 2021; Conlin et

al. 2024). In the context of T2DM, this paradigm necessitates adaptive models capable of reflecting individual physiological responses, lifestyle behaviours, and treatment adherence over time.

From a socio-technical perspective, healthcare systems are understood as complex interactions between human actors, digital technologies, organisational processes, and regulatory constraints (Jørgensen et al. 2023). DTs align with this view by enabling computational representations that integrate clinical data, sensor streams, and behavioural inputs to support predictive analytics and scenario simulation (Vallée 2023; Laubenbacher et al. 2024). However, socio-technical theory also highlights that technological intelligence alone is insufficient; governance mechanisms must ensure trust, accountability, and alignment with institutional and ethical norms.

Trusted digital infrastructure theory provides the foundation for addressing these governance requirements. Blockchain technology has been extensively studied as an enabling mechanism for decentralised trust, offering cryptographic guarantees of data integrity, transparent auditability, and enforceable access control without reliance on a single central authority (Chen et al. 2018; Yaqoob et al. 2021). In healthcare, permissioned blockchain architectures are particularly relevant, as they support controlled participation, regulatory compliance, and patient-centric consent management (Tanwar et al. 2020; Gupta et al. 2024). These properties directly address concerns related to data sharing, consent traceability, and accountability in distributed healthcare ecosystems.

TABLE 1. Comparative analysis of representative DTs– and blockchain-based healthcare frameworks, highlighting limitations in end-to-end integration for T2DM management

No.	Reference	Clinical Domain	DTs Personalisation	Data Governance Mechanism	Consent Traceability	Interoperability Support	Decision-Support Integration	Validation Level
1	Chen et al. (2018)	General healthcare	None	Permissioned blockchain	Implicit	Not specified	None	Conceptual
2	Tanwar et al. (2020)	Healthcare data sharing	None	Permissioned blockchain	Explicit (policy-based)	Not specified	None	Conceptual
3	Huang et al. (2020)	Electronic health records	None	Hybrid (blockchain + cloud)	Explicit (access logs)	Proprietary	None	Prototype
4	Yaqoob et al. (2021)	Healthcare systems	None	Permissioned blockchain	Not addressed	Not specified	None	Survey
5	Vallée (2023)	Chronic disease (general)	Patient-specific (dynamic)	None	Not addressed	Proprietary	Offline analytics	Conceptual
6	Meijer et al. (2023)	Digital health	Partial (population-level)	None	Not addressed	Not specified	Offline analytics	Simulation
7	Okegbile et al. (2023)	Smart healthcare	Partial (sensor-driven)	Centralised	Implicit	Proprietary	Offline analytics	Prototype
8	Zhang et al. (2024)	Diabetes management	Patient-specific (dynamic)	None	Not addressed	Proprietary	Real-time clinical support	Simulation
9	Karamanos et al. (2025)	T2DM	Patient-specific (dynamic)	None	Not addressed	Not specified	Real-time clinical support	Simulation
10	Amofa et al. (2024)	Smart healthcare	Partial (rule-based)	Permissioned blockchain	Explicit (smart contract–based)	Not specified	None	Prototype
11	Gahlawat & Tanwar (2025)	Healthcare data governance	None	Permissioned blockchain	Explicit (smart contract–based)	Not specified	None	Prototype

Taken together, these theoretical perspectives suggest that effective digital transformation in T2DM management requires the coordinated integration of personalisation and governance. DTs provide the analytical and predictive capabilities necessary for individualised care, while blockchain-based infrastructures establish the trust, transparency, and security required for sustainable deployment. Prior studies have largely operationalised these theories in isolation, resulting in fragmented solutions that either prioritise clinical intelligence without robust governance or focus on data security without meaningful decision support.

TRANSITION TO THE CONCEPTUAL FRAMEWORK

The synthesis of the theoretical foundations and the critical gaps identified in the literature motivates the need for an integrated conceptual framework. As demonstrated in the comparative analysis of existing studies (Table 1), current DTs–based healthcare solutions often lack explicit mechanisms for consent governance, auditability, and interoperability, while blockchain-centric approaches provide secure data management but offer limited support for patient-specific modelling and clinical decision-making. This separation undermines the practical realisation of patient-centric, trustworthy, and scalable T2DM management systems.

To address these limitations, the proposed conceptual framework is designed to operationalise the complementary strengths of DTs and blockchain within a unified architecture. The framework aligns patient-centric care principles with socio-technical and trusted infrastructure theories by coupling continuous data acquisition and personalised DTs modelling with blockchain-enforced access control, consent traceability, and transparent audit mechanisms. Interoperability standards are incorporated to enable seamless data exchange across devices and healthcare systems, supporting longitudinal patient monitoring and cross-organisational collaboration.

Accordingly, the conceptual framework presented in the following section translates theoretical insights into a structured system architecture that supports secure, transparent, and personalised T2DM management. By explicitly linking theory to design, the framework establishes a foundation for future implementation, empirical evaluation, and clinical validation of DTs–enabled, blockchain-governed healthcare systems.

PROPOSED CONCEPTUAL FRAMEWORK

DESIGN RATIONALE AND THEORETICAL ALIGNMENT

The proposed conceptual framework is designed to operationalise the theoretical principles of patient-centric care, socio-technical systems, and trusted digital infrastructures discussed in the preceding section. Patient-centric care theory requires continuous personalisation, anticipatory decision-making, and meaningful patient involvement in disease management (Daly & Hovorka 2021; Conlin et al. 2024). Socio-technical theory emphasises the need to integrate technological intelligence with human actors, organisational processes, and regulatory constraints (Jørgensen et al. 2023). Trusted digital infrastructure theory further necessitates transparent governance mechanisms to ensure data integrity, accountability, and consent enforcement in distributed systems (Chen et al. 2018; Yaqoob et al. 2021).

In response to these theoretical requirements and the gaps identified in existing studies (Table 1), the proposed framework integrates patient-specific DTs with a permissioned blockchain infrastructure to support secure, transparent, and personalised T2DM management. Rather than treating DTs and blockchain as independent components, the framework explicitly couples clinical intelligence with governance mechanisms, ensuring that personalisation and trust co-evolve within a unified system architecture. To ensure traceability between the theoretical foundations and the proposed system architecture, Table 2 maps key theoretical constructs to corresponding design principles and framework components. An overview of the proposed framework and its core components is illustrated in Figure 2, which depicts the interaction between data sources, DTs modelling, blockchain-based governance, and clinical decision support.

TABLE 2. Mapping of theoretical foundations to architectural components of the proposed conceptual framework

Theoretical Foundation	Design Principle	Framework Component	Functional Role in T2DM Management
Patient-centric care	Personalisation and shared decision-making	Patient-specific DTs	Adaptive modelling of glucose dynamics and treatment response
Socio-technical systems	Human–technology integration	Data acquisition & integration layer	Continuous capture of clinical, sensor, and behavioural data
Trusted digital infrastructure	Transparency and accountability	Permissioned blockchain layer	Consent enforcement, access control, auditability
Privacy-by-design	Minimum disclosure	ZKP-enabled verification	Secure proof of compliance without data exposure
Interoperability theory	Standards-based exchange	HL7/FHIR interfaces	Cross-system data integration and continuity of care

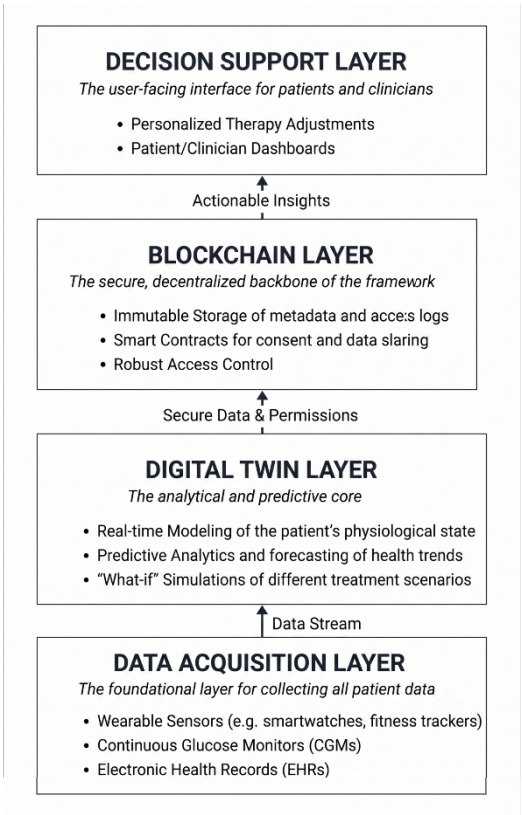


FIGURE 1. T2DM Management Framework Architecture

FRAMEWORK ARCHITECTURE OVERVIEW

As shown in Figure 1, the framework comprises four tightly integrated layers: (i) data acquisition and integration, (ii) patient-specific DTs modelling, (iii) blockchain-enabled governance and security, and (iv) clinical decision support and stakeholder interaction. Each layer is designed to fulfil a distinct theoretical role while supporting end-to-end T2DM management.

DATA ACQUISITION AND INTEGRATION LAYER

The data acquisition layer aggregates heterogeneous data streams relevant to T2DM management, including continuous glucose monitoring, wearable sensor data, electronic health records, laboratory results, and patient-reported lifestyle information. Consistent with socio-technical principles, this layer supports both automated sensing and human input, enabling longitudinal monitoring of physiological and behavioural factors (Lu et al. 2024; Liakos et al. 2023). To address interoperability challenges identified in prior studies, the framework adopts standards-based data representations, facilitating seamless data exchange across devices and healthcare information systems.

PATIENT-SPECIFIC DIGITAL TWINS LAYER

At the core of the framework lies the patient-specific DTs, which dynamically represents an individual's metabolic state, treatment response, and behavioural patterns. The DTs is continuously updated using incoming data streams, enabling predictive analytics, risk assessment, and simulation of alternative intervention strategies (Vallée, 2023; Zhang et al. 2024). In line with patient-centric care theory, this layer supports personalised treatment planning by allowing clinicians and patients to explore "what-if" scenarios, such as medication adjustments or lifestyle changes, without direct clinical risk (Karamanos et al. 2025).

Importantly, the DTs layer is designed to function within clearly defined governance constraints. Access to model outputs and underlying data is mediated by blockchain-enforced policies, ensuring that personalisation does not compromise patient privacy or data sovereignty.

The Digital Twin maintains a dynamic representation of the patient's physiological state through periodic synchronization with data generated by IoT-enabled monitoring devices and healthcare information systems. Synchronization frequency is determined according to the clinical significance and temporal characteristics of each data source. Continuous physiological measurements such as glucose levels, heart rate, and physical activity are synchronized at intervals ranging from 12 to 24 hours, consistent with typical wearable or bedside sensing capabilities. Blood pressure measurements are synchronized whenever new readings become available, while Electronic Health Record (EHR) data are synchronized using an event-driven mechanism. The framework therefore adopts a near-real-time synchronization model, targeting an update latency of between 12 to 24 hours for required physiological variables.

This adaptive synchronization approach balances computational efficiency, communication overhead, and Digital Twin fidelity while ensuring that decision-support recommendations are generated using the most current patient information available.

ADAPTIVE MODEL UPDATING USING MOVING HORIZON ESTIMATION

Maintaining the fidelity between the physical patient and the Digital Twin, the framework employs a Moving Horizon Estimation (MHE) approach for continuous model adaptation. The Digital Twin is represented using a physiology informed model whose parameters are periodically recalibrated using recent patient observations. At each synchronization interval, the estimator considers

a finite horizon of recent measurements and solves an optimization problem:

$$\min_{\theta} \sum_{k=t-N}^{t} (y_k - \hat{y}_k(\theta))^2 \quad (1)$$

where:

y_k denotes observed physiological measurements,

$\hat{y}_k$ denotes model-predicted values,

θ represents patient-specific physiological parameters,

N denotes the estimation horizon.

The resulting parameter estimates are used to update the Digital Twin state and maintain alignment with the patient's evolving physiological condition. This process enables adaptation to changes arising from aging, medication adjustments, lifestyle modifications, and disease progression while reducing the risk of model drift.

BLOCKCHAIN-ENABLED GOVERNANCE AND SECURITY LAYER

The governance layer leverages a permissioned blockchain architecture to enforce access control, consent management, and auditability across the framework. Drawing on trusted digital infrastructure theory, this layer provides cryptographic guarantees of data integrity and transparent logging of all data-related events (Chen et al. 2018; Tanwar et al. 2020). Smart contracts are employed to implement role-based access control and to record patient consent in a versioned, time-stamped, and immutable manner, supporting explicit consent traceability and regulatory compliance (Yaqoob et al. 2021; Gupta et al. 2024).

By decoupling data storage from governance logic, the blockchain layer enables secure sharing of sensitive health data without exposing raw patient information on chain. This design aligns with socio-technical considerations by balancing technical enforcement with institutional and ethical requirements for privacy, accountability, and trust (Jørgensen et al. 2023).

CLINICAL DECISION SUPPORT AND STAKEHOLDER INTERACTION LAYER

The final layer translates DTs outputs into clinically actionable insights for patients, clinicians, and other authorised stakeholders. Decision-support functionalities include personalised alerts, treatment recommendations, and longitudinal trend visualisation, enabling proactive T2DM management rather than reactive intervention (Maina et al. 2023; Conlin et al. 2024). Patients are empowered to engage with their own data and DTs representations, reinforcing shared decision-making and self-management capabilities.

All interactions within this layer are governed by blockchain-enforced access policies, ensuring that recommendations and data views are delivered only to authorised parties with valid consent. This tight coupling between decision support and governance directly addresses limitations observed in prior DT-only and blockchain-only approaches (Amofa et al. 2024; Gahlawat & Tanwar 2025).

BLOCKCHAIN-SUPPORTED CLINICIAN–DIGITAL TWIN INTERACTION

The blockchain layer serves as an off-channel governance, authorization, and audit mechanism supporting interactions between clinicians and Digital Twin agents. As illustrated in Figure 2, when a clinician requests patient-specific simulations or recommendations, a smart contract automatically verifies their credentials against patient consent policies. Once this request is validated, the blockchain forwards the approval to the Digital Twin platform. The platform then securely interacts with associated healthcare information systems to retrieve necessary physiological data and generate the requested simulation output.

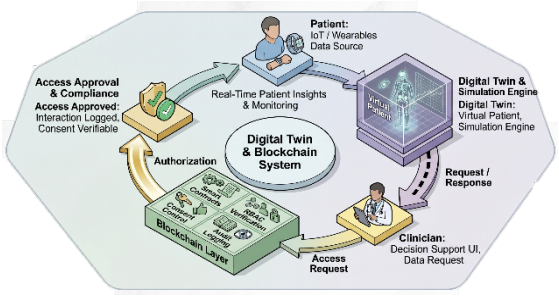


FIGURE 2. Blockchain supported communication workflow between clinicians and Digital Twin agents

This architecture splits data handling to balance performance and security: immutable transaction logs (metadata, identifiers, and access decisions) are recorded on-chain, whereas sensitive clinical files remain off-chain for privacy and scalability. This setup provides transparent, real-time access to Digital Twin services under tight patient governance. Furthermore, smart contracts formalize this environment by programming the organizational trust dynamics derived from the validated KMS diabetes self-management model directly into system-enforced governance policies.

ILLUSTRATIVE USE CASE: A PATIENT'S JOURNEY THROUGH THE FRAMEWORK

This case study outlines the profile and initial digital monitoring journey of Kesavan, a 58-year-old male with a 3-year history of T2DM. This profile is designed for a digital health platform integrating wearable data, self-reported metrics, and clinical records to support proactive and personalized care.

Clinical History and Baseline Data
Patient Demographics:
Name: Kesavan Age: 58 years Occupation: Retired marketing executive Primary Care Physician (PCP): Dr. Anya Sharma Medical History: Kesavan's medical history includes several comorbidities commonly associated with T2DM: Hypertension (diagnosed at age 53) Hyperlipidaemia (diagnosed at age 55) Obstructive sleep apnea (diagnosed at age 56), managed with a continuous positive airway pressure (CPAP) machine.
Current Medications:
Metformin 1000 mg, twice daily Lisinopril 20 mg, once daily Atorvastatin 40 mg, once daily
Social History:
Kesavan is a former smoker who quit 10 years ago. He reports moderate alcohol consumption (1-2 glasses of wine on weekends). He lives with his wife and maintains an active lifestyle, enjoying gardening and walking his dog.
Quarterly Lab Assessment (Baseline):
At his last quarterly check-up, Kesavan's glycated haemoglobin (HbA1c) was 7.8%, exceeding the target of <7.0%. Other key results included a fasting plasma glucose (FPG) of 145 mg/dL and an LDL-C of 115 mg/dL

The journey for Kesavan begins with data collection. His wearable device continuously streams activity, heart rate, and sleep data, while his smartphone app logs self-monitored glucose readings and meal details. This real-time information, combined with his historical EHR data and quarterly lab results (HbA1c=7.8%), populates the foundational Data Acquisition Layer and fuels his DTs.

Next, the DTs Layer processes this data. The DTs identifies a key pattern: Kesavan's blood glucose is consistently high before dinner, correlating with a recent drop in his daily step count. The DTs then runs a predictive simulation, modelling the effect of a simple intervention, such as a 15-minute post-dinner walk, on his glycaemic control. Simultaneously, for Dr. Sharma to access these new, sensitive insights, the framework's Blockchain Layer is activated. A smart contract securely manages Kesavan's consent, creating an immutable record that verifies his permission for Dr. Sharma to view his data and the DTs' output.

With consent confirmed, the DT's insights are delivered to Dr. Sharma via the Decision Support Layer. The dashboard highlights the DTs' simulation, showing the potential for improved glycaemic control with the post-dinner walk. This forms the basis for a therapy adjustment. Dr. Sharma can then formally recommend this simple lifestyle change to Kesavan. The cycle closes with continuous feedback as Kesavan's new walking routine is captured by his wearable, and this data is fed back into the DTs. The DTs continually validate its initial prediction and refines its model, ensuring the system remains adaptive and personalized to Kesavan's evolving health needs.

SUMMARY AND LINK TO SUBSEQUENT SECTIONS

By integrating patient-specific DTs with blockchain-based governance mechanisms, the proposed conceptual framework provides a theoretically grounded foundation for secure, transparent, and personalised T2DM management. The framework explicitly translates patient-centric, socio-technical, and trusted infrastructure theories into an end-to-end system architecture that addresses both clinical intelligence and data governance requirements.

The security, privacy, and trust implications of this framework are examined in detail in the subsequent section, where blockchain-enforced access control, auditability, and advanced cryptographic protections are discussed.

SECURITY, PRIVACY AND TRUST MECHANISMS

BLOCKCHAIN-BASED ACCESS CONTROL AND AUDITABILITY

The confidentiality, integrity, and availability of patient data are fundamental requirements in digital healthcare systems, particularly for chronic, data-intensive conditions such as T2DM (Chen et al. 2018; Yaqoob et al. 2021). As healthcare increasingly relies on predictive analytics, automated decision support, and cross-organizational data sharing, these classical security properties must be complemented by transparency to establish trust among patients, clinicians, researchers, and regulatory authorities (Jørgensen et al. 2023; Gupta et al. 2024). In distributed digital health ecosystems, stakeholders must be able to verify how data are accessed, how consent is enforced, and

how governance decisions evolve over time, without compromising patient privacy.

Transparency in the proposed framework refers to the verifiable visibility of data access, consent decisions, and system interactions across the T2DM care lifecycle. It is operationalized through two complementary mechanisms: auditability and consent traceability. Auditability ensures that all data-related events, including data ingestion, access requests, consent updates, and system interactions, are immutably recorded on a permissioned blockchain, enabling authorized stakeholders to retrospectively reconstruct and verify system behaviour (Chen et al. 2018; Tanwar et al. 2020). Consent traceability guarantees that patient consent is explicitly recorded, versioned, and time-stamped via smart contracts, allowing every instance of data access or sharing to be cryptographically linked to a valid consent state in compliance with healthcare regulations such as GDPR and HIPAA (Huang et al. 2020; Yaqoob et al. 2021).

To enforce these principles, the framework adopts a Role-Based Access Control (RBAC) model that is programmatically implemented through smart contracts on a permissioned blockchain. Users are assigned predefined roles, such as patient, clinician, researcher, or system administrator, each associated with specific access privileges. This approach ensures that clinicians can access patient-specific DTs models and recent clinical data, while researchers may be restricted to anonymized or aggregated datasets only (Amofa et al. 2024; Gahlawat & Tanwar 2025). All permission grants, modifications, and revocations are recorded on the immutable ledger, providing enforceable and auditable access governance.

Patient data are further protected using layered cryptographic safeguards. Data transmitted from wearable devices and sensors are encrypted in transit using secure communication protocols such as Transport Layer Security (TLS), mitigating risks of interception or tampering (Prasat et al. 2022; Wu et al. 2024). Sensitive health data stored off-chain in secure repositories or private cloud environments are encrypted at rest, typically using symmetric encryption schemes, where plaintext data are transformed into ciphertext using a secret key. Encryption key management is governed by smart contracts, reducing reliance on centralized authorities and preventing single points of failure (Huang et al. 2020; Yaqoob et al. 2021).

Finally, the immutable nature of blockchain technology provides a comprehensive and tamper-evident audit trail. Every data transaction, access request, consent update, and governance action is permanently recorded on the ledger, supporting accountability and regulatory compliance (Chen et al. 2018; Tanwar et al. 2020). Cryptographic hashes anchored on the blockchain further ensure data integrity, making unauthorized data modification detectable and strengthening trust in the DTs–enabled decision-support process (Amofa et al. 2024).

CRYPTOGRAPHIC PROTECTIONS AND ZERO-KNOWLEDGE PROOFS

While access control, encryption, and auditability provide strong baseline security, certain healthcare scenarios require selective disclosure of information without revealing sensitive underlying data. Zero-Knowledge Proofs (ZKPs) offer an advanced cryptographic mechanism to address this challenge by allowing one party to prove the validity of a statement without disclosing any additional information (Yaqoob et al. 2021; Ghanmi et al. 2025).

Within the proposed T2DM framework, ZKPs can be used to verify compliance with predefined health or behavioural criteria without exposing granular patient data. For example, a patient may demonstrate adherence to a treatment plan or confirm that their average glucose levels over a specific period fall within an agreed threshold, without revealing detailed continuous glucose monitoring (CGM) records. Such selective disclosure mechanisms preserve patient privacy while enabling verifiable interactions with clinicians, insurers, or other authorized stakeholders (Huang et al. 2020; Ghanmi et al. 2025).

The security guarantees of ZKPs are based on three fundamental properties:

1. Completeness, whereby a truthful statement can be successfully verified.
2. Soundness, ensuring that false statements cannot be falsely validated; and
3. Zero-knowledge, whereby no information beyond the statement's validity is revealed.

In the proposed architecture, ZKPs are positioned as an optional, advanced privacy-enhancing mechanism, complementing the core blockchain-based security and governance infrastructure rather than replacing it. Their selective adoption enables a flexible balance between data utility, regulatory compliance, and patient confidentiality, particularly in multi-stakeholder healthcare ecosystems where trust boundaries and information asymmetry are prominent (Yaqoob et al. 2021; Jørgensen et al. 2023).

PERSONALIZATION AND CLINICAL DECISION SUPPORT

PATIENT-SPECIFIC DIGITAL TWINS MODELLING

The core of a patient-centric framework for T2DM lies in its ability to provide highly personalized care. This is

achieved through two synergistic mechanisms: the use of individualized simulation parameters within the DTs and the implementation of adaptive feedback loops. These mechanisms move beyond a "one-size-fits-all" approach to a model that is uniquely tailored to each patient's biology and behaviour.

As introduced earlier, DTs is not a generic model but a high-fidelity, patient-specific virtual replication. This is made possible by initializing its core parameters with a diverse and comprehensive set of data points unique to an individual. These parameters go beyond basic clinical metrics and include multi-omics data (e.g., genetic predispositions, gene expression profiles), detailed historical clinical data from EHRs (e.g., medication history, comorbidity profiles), and continuous real-time data from sensors (e.g., CGM glucose readings, heart rate variability from wearables). The individualized DTs can be conceptually represented as a function where its state is a product of these unique inputs:

$$\min_{\theta} \sum_{k=t-N}^{t} (y_k - \hat{y}_k(\theta))^2 \quad (2)$$

Here, $\theta_{patient}$ represents a set of patient-specific parameters that fine-tune the predictive and mechanistic models of the DTs. This level of personalization is critical for performing accurate "what-if" simulations, as it allows clinicians to predict a patient's specific physiological response to an intervention (e.g., a specific drug, a tailored exercise plan) before it is prescribed. Without these individualized parameters, the DTs' predictions would be generalized and potentially inaccurate, undermining its clinical utility.

ADAPTIVE PERSONALIZATION AND PREDICTIVE SIMULATION

The framework's ability to evolve with the patient's condition is driven by a continuous, adaptive feedback loop. This mechanism ensures that the DTs remains accurate and relevant over time. The loop operates as follows:

1. Data Collection: The system continuously ingests real-time data streams from wearables and CGM, reflecting the patient's current state and their response to interventions.
2. Model Update: This new data is used to recalibrate and refine the DTs' predictive models. This is an essential process to prevent model drift, where a static model becomes less accurate as the patient's physiology and lifestyle change over time.
3. Actionable Insight: The DTs generates a new set of personalized insights or recommendations, which are then delivered to the patient and clinician via the Decision Support Layer.
4. Intervention & Monitoring: The patient or clinician acts on the recommendation, and the DT begins to monitor the impact of this intervention in real-time, feeding this new data back into the start of the loop.

PHYSIOLOGICAL MODELING OF PATIENT STATE

The Digital Twin represents the patient's physiological state using a mechanistic model of glucose regulation. Rather than relying solely on data-driven machine learning methods, the framework adopts a physiology-informed approach in which patient-specific variables are represented through ordinary differential equations describing glucose dynamics.

A simplified formulation may be expressed as:

$$\frac{dG(t)}{dt} = R_{meal}(t) - U_{glucose}(t) - E_{activity}(t) \quad (3)$$

where:

$G(t)$denotes blood glucose concentration,

$R_{meal}(t)$ represents glucose influx from dietary intake,

$U_{glucose}(t)$ represents baseline glucose utilization,

$E_{activity}(t)$ represents additional glucose consumption induced by physical activity.

In the illustrative scenario, a 15-minute walking session increases $E_{activity}(t)$, resulting in enhanced glucose uptake and a corresponding reduction in predicted blood glucose concentration. Patient-specific parameters governing glucose utilization and activity response are continuously updated through the MHE approach described previously.

The use of estimation algorithm provides interpretability and physiological plausibility while enabling personalized "what-if" simulations. Future work will investigate hybrid Digital Twin architectures combining mechanistic metabolic models with machine learning approaches for enhanced predictive performance. This cycle of continuous learning allows the framework to dynamically adjust care plans based on observed outcomes. For instance, if a predicted dietary change does not yield the expected glycaemic response, the DTs adapt its model to better understand the patient's unique metabolic profile, generating a more accurate prediction for the next iteration. This ensures the system is not only

personalized at the outset but remains so throughout the entire course of treatment.

STAKEHOLDER ECOSYSTEM AND VALUE PROPOSITION

The proposed framework's success hinges on a multi-stakeholder ecosystem where each entity plays a distinct role, facilitated by the architecture's core features. Patients are at the centre, serving as the source of real-time data and the primary beneficiaries. Their active participation and secure ownership of data, managed by blockchain smart contracts, are crucial for the DTs' accuracy and for enabling personalized care. Clinicians leverage the framework as a powerful decision-support tool. They utilize the DTs' predictive analytics and "what-if" simulations to move beyond reactive care, making evidence-based, personalized therapeutic adjustments. Researchers gain secure, consent-based access to high-quality, longitudinal datasets.

This accelerates discoveries related to T2DM mechanisms and population health, all while maintaining patient privacy through immutable audit trails. Insurers can use the verifiable and transparent data to develop value-based care models and patient engagement incentives. The potential for improved health outcomes may lead to significant long-term cost reductions. Regulatory Bodies ensure compliance with critical data privacy laws like HIPAA and GDPR. Their oversight establishes trust, ethical guidelines, and is essential for the framework's widespread adoption and integration into existing healthcare systems.

IMPLEMENTATION CONSIDERATION

Having outlined the conceptual framework, this section critically examines the practical challenges and key considerations for implementing a blockchain-integrated DTs in a real-world T2DM management ecosystem.

Implementing a blockchain-integrated DTs framework for T2DM management requires careful consideration of several technical, regulatory, and financial factors. From a technical standpoint, the architecture must balance the computational demands of the DTs with the need for real-time responsiveness. This necessitates a strategic blend of edge processing for low-latency tasks like real-time alerts and cloud-based processing for resource-intensive "what-if" simulations and complex AI modelling. The blockchain component requires an equally pragmatic approach. Public chains are impractical due to low throughput and high energy consumption. Instead, a consortium or permissioned blockchain using efficient consensus mechanisms like Proof-of-Stake (PoS) or Practical Byzantine Fault Tolerance (PBFT) is proposed, offering high scalability and lower operational costs.

Beyond technical infrastructure, a critical consideration is data quality and model accuracy. The effectiveness of the DTs is contingent on robust mechanisms for handling missing or noisy data and, most importantly, continuous validation to prevent model drift. These measures are not only technical but also have significant ethical implications. The framework must be designed to align with strict regulatory standards like HIPAA and GDPR, with the blockchain acting as a secure, immutable audit trail for consent management and access control. Ethical considerations also extend to ensuring the DTs models are free from bias and that simulations are presented as decision-support tools rather than prescriptive commands.

Finally, the framework's adoption hinges on its ability to integrate seamlessly with existing healthcare systems and provide a compelling cost–benefit analysis. This requires adhering to FHIR for standardized data exchange with EHRs. While the initial infrastructure investment is substantial, the long-term potential for improved patient outcomes and significant cost savings from preventing expensive complications and hospitalizations makes the framework a potentially valuable and transformative investment.

DISCUSSION

INTEGRATIVE INSIGHTS: WHY DIGITAL TWINS AND BLOCKCHAIN MATTER FOR T2DM

The comparative analysis presented in Table 1 highlights a central challenge in the digital transformation of T2DM management: the need to reconcile personalized clinical decision-making with robust data security, governance, and trust. Across the reviewed literature, DTs are predominantly employed to support patient-specific modelling, including glucose dynamics simulation, treatment optimization, and continuous physiological monitoring (Karamanos et al. 2025; Tandon et al. 2025; Zhang et al. 2024). These studies demonstrate the strength of DTs in capturing individual variability and enabling predictive, data-driven care. However, many DT-based solutions implicitly assume the availability of secure, interoperable, and trusted data infrastructures, an assumption that is rarely satisfied in real-world healthcare environments (Meijer et al. 2023; Katsoulakis et al. 2024).

In contrast, blockchain-oriented studies focus primarily on strengthening data governance through secure data sharing, decentralized access control, auditability, and patient-managed consent mechanisms (Amofa et al. 2024; Gahlawat & Tanwar, 2025; Yaqoob et al. 2021).

Permissioned blockchain architectures and smart contracts are frequently proposed to address privacy, trust, and regulatory compliance concerns in distributed healthcare ecosystems. While these approaches provide a strong foundation for data integrity and accountability, they typically operate independently of advanced patient modelling and predictive analytics, limiting their contribution to personalized clinical decision support.

Synthesizing the findings in Table 1 reveals that neither technology, when deployed in isolation, is sufficient to address the longitudinal, data-intensive, and multi-stakeholder nature of T2DM management. DT-driven systems without integrated governance mechanisms face persistent challenges related to data provenance, consent enforcement, and interoperability, whereas blockchain-based solutions without patient-specific modelling struggle to translate secure data handling into clinically actionable insights. This separation between personalization and security represents a fundamental limitation of existing approaches. Consequently, a co-designed integration of DTs and blockchain is required to simultaneously support individualized care and trustworthy data management. This integrative perspective provides the conceptual foundation for the proposed framework discussed earlier and motivates a critical examination of its limitations, implementation considerations, and future research needs.

CHALLENGES AND LIMITATIONS OF DIGITAL TWINS AND BLOCKCHAIN IN T2DM MANAGEMENT

Despite their complementary strengths, the integration of DTs and blockchain technologies in T2DM management faces several technical, organizational, and ethical challenges. One key limitation concerns data quality and heterogeneity. DTs rely on continuous, high-fidelity data streams from electronic health records, wearable sensors, and patient-reported inputs. In practice, such data are often incomplete, noisy, and inconsistently formatted, which can compromise model accuracy and reliability (Meijer et al. 2023; Okegbile et al. 2023). These challenges are further exacerbated in chronic disease contexts, where patient behaviour, treatment regimens, and physiological responses evolve over long time horizons.

Interoperability remains another significant barrier. Healthcare systems typically operate across fragmented platforms and standards, limiting seamless data exchange and integration. While blockchain can enhance data provenance and access control, it does not inherently resolve semantic interoperability or standardization issues required for effective DT updating and inference (Yaqoob et al. 2021; Gupta et al. 2024). Without alignment to established healthcare data standards, integrated DT–blockchain systems risk becoming technically secure yet operationally siloed.

Ethical and regulatory considerations also pose substantial challenges. Patient-centric DTs raise concerns related to transparency, explainability, and accountability, particularly when predictive models influence clinical decisions (Drummond & Gonsard, 2024; Ghanmi et al. 2025). Similarly, blockchain-based consent mechanisms must balance immutability with patients' rights to data modification or withdrawal, as required by healthcare regulations. These tensions highlight the need for governance models that extend beyond technical design to encompass legal and ethical oversight.

Finally, scalability and computational overhead represent practical limitations. Continuous DT simulation and blockchain transaction processing may introduce latency, cost, and energy consumption concerns, especially in large-scale deployments (Amofa et al. 2024; Roopa & Venugopal, 2025). Addressing these limitations is essential to ensure that integrated solutions remain viable beyond controlled experimental settings.

CONNECTIVITY AWARE DEPLOYMENT FOR RESOURCE CONSTRAINED ENVIRONMENTS

Although the proposed framework supports near-real-time synchronization, continuous internet connectivity may not be available in all deployment settings. This challenge is particularly relevant in rural and low-resource regions where network coverage may be intermittent. To accommodate such environments, the framework uses an edge-assisted, store-and-forward architecture to handle intermittent network coverage in rural or low-resource regions. IoT devices and local gateways temporarily encrypt and store physiological measurements during outages. Since data is only sampled every 12 to 24 hours, accumulated logs are efficiently uploaded upon reconnection. Meanwhile, the Digital Twin simulates outcomes based on the latest available patient state, tracking synchronization delays so clinicians can gauge data freshness. Ultimately, this hybrid offline-online strategy ensures that infrastructure limitations do not restrict patient participation. The ability to operate under intermittent connectivity conditions is consistent with the patient-centric philosophy of the previously validated diabetes self-management model, ensuring that participation in monitoring activities is not constrained by digital infrastructure limitations.

IMPLEMENTATION AND DEPLOYMENT CONSIDERATIONS

Translating integrated DT–blockchain frameworks from conceptual designs into real-world T2DM care settings requires careful consideration of implementation and deployment constraints. One critical factor is alignment with existing clinical workflows. Healthcare professionals operate under time, regulatory, and resource constraints, and any digital solution that disrupts established practices risks limited adoption (Chen et al. 2022; Khater et al. 2024, Abd Mutalib et al. 2025). Integrated systems must therefore be designed to complement, rather than replace, clinician decision-making processes.

Infrastructure readiness is another important consideration. The deployment of DTs and blockchain platforms demands reliable digital infrastructure, including secure data storage, network connectivity, and computational resources. In many healthcare settings, particularly in low- and middle-income regions, such infrastructure may be unevenly available, limiting scalability and equity of access (Maina et al. 2023; Wahyudi, 2024).

Stakeholder acceptance also plays a crucial role. Patients must trust that DT-driven insights and blockchain-based governance mechanisms genuinely serve their interests, while clinicians must perceive added clinical value rather than increased administrative burden. Clear communication, explainable models, and transparent consent processes are therefore essential to foster adoption (Jørgensen et al. 2023; Drummond & Gonsard, 2024).

Finally, cost and sustainability considerations cannot be overlooked. Integrated DT–blockchain systems may introduce additional development, maintenance, and training costs. Long-term sustainability will depend on demonstrating tangible clinical benefits, cost-effectiveness, and alignment with healthcare reimbursement and policy frameworks (Vrangbæk, 2021; Conlin et al. 2024).

FUTURE RESEARCH DIRECTIONS

The analysis presented in this study highlights several promising directions for future research. First, there is a need for longitudinal clinical validation of DT–blockchain systems in real-world T2DM care settings. Most existing studies remain at the conceptual or proof-of-concept stage, underscoring the importance of empirical evidence demonstrating clinical effectiveness, safety, and patient outcomes (Karamanos et al. 2025; Zhang et al. 2024).

As the proposed framework represents the technological evolution of a previously validated collaborative Knowledge Management System (KMS) model for Type 2 Diabetes self-management, future pilot studies should evaluate both healthcare outcomes and knowledge management effectiveness. Clinical performance expected to be assessed using established diabetes indicators such as Time in Range (TIR), HbA1c reduction, fasting blood glucose levels, blood pressure control, and the frequency of hypoglycaemic events. The Digital Twin component to be evaluated through synchronization latency, state estimation accuracy, adaptation performance, and data completeness, while the blockchain layer may be assessed through consent compliance, access authorization accuracy, auditability, and data integrity verification.

In addition, the pilot evaluation should retain key constructs identified in the original KMS study, including perceived usefulness, user satisfaction, knowledge quality, and system utilization, to determine whether the integration of Digital Twin and blockchain technologies enhances patient engagement and collaborative self-management. Patient trust in Digital Twin recommendations, clinician acceptance, and recommendation adoption rates should also be examined as indicators of successful technology adoption. Collectively, these measures would provide a comprehensive assessment of the framework's clinical effectiveness, technological performance, governance capabilities, and contribution to knowledge-driven diabetes self-management.

Third, future work should explore adaptive and explainable DT models that evolve alongside patients' changing physiological states and treatment responses. Enhancing transparency and interpretability will be critical to supporting clinician trust and ethical deployment (Laubenbacher et al. 2024; Drummond & Gonsard, 2024).

Fourth, research is needed to develop standardized interoperability frameworks that align DTs–blockchain architectures with existing healthcare data standards and regulatory requirements. Such efforts would facilitate broader integration across healthcare systems and improve scalability (Gupta et al. 2024; Yaqoob et al. 2021).

Finally, interdisciplinary collaboration among clinicians, engineers, data scientists, and policymakers will be essential to address the socio-technical complexities of integrated digital health systems. Future research should therefore extend beyond technical innovation to encompass governance, policy, and ethical dimensions of DTs–blockchain-enabled T2DM management.

CONCLUSION

This framework establishes a reference architecture for secure, adaptive DTs deployment in chronic disease management. The synergy between the DTs' predictive simulations and the blockchain's secure, transparent data

governance addresses a critical gap in current healthcare models. This architecture moves beyond reactive, population-level care, enabling a proactive, patient-centric approach that anticipates health events and optimizes treatment based on individual physiology.

The implications for chronic disease management are profound. This model provides a scalable blueprint for personalized medicine, re-establishing patient control over their health data and fostering a trust-based ecosystem. To realize this vision, we call for multidisciplinary collaboration among clinical, technical, and regulatory experts. The next critical step is to launch pilot studies to validate the framework's clinical utility and pave the way for its transformative adoption in modern healthcare.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support provided by SK Innovation Sdn. Bhd under grant number KK-2022-001

DECLARATION OF COMPETING INTEREST

None.

REFERENCES

Abd Mutalib, M. A., Zainul Azlan, N., Norsahperi, N. M. H., & Ibrahim Hassan, H. 2025. Quantitative measure of the Functional Ability Index using activity of daily living based on motor activity log. *Jurnal Kejuruteraan* 37(6): 2657–2665.

Ahmad, E., Lim, S., Lamptey, R., Webb, D. & Davies, M. 2022. Type 2 diabetes. *The Lancet* 400: 1803–1820.

Ahmed, A.M.S. & Chellappan, K. 2013. Pervasive collaborative network approach to type II diabetes management. *Asian Transactions on Basic and Applied Sciences* 3(2): 53–58.

Amofa, S., Serhani, M.A., Elnaffar, S. & Alghamdi, A. 2024. A patient-centric digital twin framework for secure healthcare data sharing using blockchain. *IEEE Access* 12: 1–15.

Chen, F., Tang, Y., Wang, C., Huang, J., Huang, C., Xie, D., Wang, T. & Zhao, C. 2022. Medical cyber–physical systems: A solution to smart health and the state of the art. *IEEE Transactions on Computational Social Systems* 9: 1359–1386.

Chen, Y., Ding, S., Xu, Z., Zheng, H. & Yang, S. 2019. Blockchain-based medical records secure storage and medical service framework. *Journal of Medical Systems* 43: 1–9.

Conlin, P., Burke, B., Hobbs, C., Hurren, K., Lang, A., Morrison, J., Spacek, L., Steil, E., Watts, S., Weinreb, J. & Pogach, L. 2024. Management of type 2 diabetes mellitus: Synopsis of the Department of Veterans Affairs and Department of Defense clinical practice guideline. *Mayo Clinic Proceedings*.

Daly, A. & Hovorka, R. 2021. Technology in the management of type 2 diabetes – present status and future prospects. *Diabetes, Obesity and Metabolism* 23: 1722–1732.

Drummond, D. & Gonsard, A. 2024. Definitions and characteristics of patient digital twins being developed for clinical use: A scoping review. *Journal of Medical Internet Research* 26.

Gahlawat, A. & Tanwar, S. 2025. Digital twins and blockchain for healthcare applications: Case studies and future perspectives. *IEEE Access* 13: 1–18.

Ghanmi, H., Ahmadjee, S. & Bahsoon, R. 2025. Evaluating explanation needs in blockchain smart contracts to reconcile surprises. *ACM Transactions on Software Engineering and Methodology*.

Gupta, K., Mishra, V. & Makkar, A. 2024. A global cybersecurity standardization framework for healthcare informatics. *IEEE Journal of Biomedical and Health Informatics*.

Huang, H., Zhu, P., Xiao, F., Sun, X. & Huang, Q. 2020. A blockchain-based scheme for privacy-preserving and secure sharing of medical data. *Computers and Security* 99: 102010.

International Diabetes Federation. 2023. *Annual report 2023*. Available at: https://idf.org (accessed 11 August 2025).

Jiang, Y., Wang, C., Wang, Y. & Gao, L. 2019. A cross-chain solution to integrating multiple blockchains for IoT data management. *Sensors* 19.

Jørgensen, C., Shukla, A. & Katt, B. 2023. Digital twins in healthcare: Security, privacy, trust and safety challenges. *Lecture Notes in Computer Science*: 140–153.

Karamanos, K., Papadopoulos, A., Psomakelis, E. & Tzovaras, D. 2025. Patient-centric digital twins for personalized type 2 diabetes management. *Frontiers in Digital Health* 7.

Katsoulakis, E., Wang, Q., Wu, H., Shahriyari, L., Fletcher, R., Liu, J., Achenie, L., Liu, H., Jackson, P., Xiao, Y., Syeda-Mahmood, T., Tuli, R. & Deng, J. 2024. Digital twins for health: A scoping review. *NPJ Digital Medicine* 7.

Khater, H., Sallabi, F., Serhani, M., Barka, E., Shuaib, K., Tariq, A. & Khayat, M. 2024. Empowering healthcare with cyber-physical systems: A systematic literature review. *IEEE Access* 12: 83952–83993.

Laubenbacher, R., Mehrad, B., Shmulevich, I. & Trayanova, N. 2024. Digital twins in medicine. *Nature Computational Science* 4(3): 184–191.

Lu, X., Xie, Q., Pan, X., Zhang, R., Zhang, X., Peng, G., Zhang, Y., Shen, S. & Tong, N. 2024. Type 2 diabetes mellitus in adults: Pathogenesis, prevention and therapy. *Signal Transduction and Targeted Therapy* 9.

Maina, P., Pienaar, M. & Reid, M. 2023. Self-management practices for preventing complications of type II diabetes mellitus in low- and middle-income countries: A scoping review. *International Journal of Nursing Studies Advances* 5.

Meijer, C., Uh, H. & Bouhaddani, E. 2023. Digital twins in healthcare: Methodological challenges and opportunities. *Journal of Personalized Medicine* 13.

Okegbile, S., Cai, J., Niyato, D. & Yi, C. 2023. Human digital twin for personalized healthcare: Vision, architecture and future directions. *IEEE Network* 37: 262–269.

Prasat, K., Sanjay, S., Ananya, V., Kannadasan, R., Rajkumar, S., Raut, R. & Selvanambi, R. 2022. Analysis of cross-domain security and privacy aspects of cyber-physical systems. *International Journal of Wireless Information Networks* 29: 454–479.

Ramlana, L. A., Wan Zakia, W. M. D., Abdul Mutalib, H., Mat Daud, M. & Mustapha, A. 2025. The impact of mobile application for ocular disease screening in community outreach program. *Jurnal Kejuruteraan* 37(2): 721–729. https://doi.org/10.17576/jkukm-2025-37(2)-13

Roopa, M. & Venugopal, K. 2025. Digital twins for cyber-physical healthcare systems: Architecture, requirements, systematic analysis and future prospects. *IEEE Access* 13: 44963–44996.

Roumeliotis, C., Dasygenis, M., Lazaridis, V. & Dossis, M. 2024. Blockchain and digital twins in smart industry 4.0: The use case of supply chain – A review of integration techniques and applications. *Designs*.

Seidu, S., Cos, X., Brunton, S., Harris, S., Jansson, S., Mata-Cases, M., Neijens, A., Topsever, P. & Khunti, K. 2020. A disease state approach to the pharmacological management of type 2 diabetes in primary care. *Primary Care Diabetes* 15(1): 31–51.

Tanwar, S., Parekh, K. & Evans, R. 2020. Blockchain-based electronic healthcare record system for healthcare 4.0 applications. *Journal of Information Security and Applications* 50.

Vallée, A. 2023. Digital twin for healthcare systems. *Frontiers in Digital Health* 5.

Vrangbæk, K. 2021. Structuring complexity? A systemic perspective on the implementation of a disease management programme for type II diabetes care in Denmark. *Health Economics, Policy and Law* 18(1).

Wahyudi, J. 2024. Self-care management of type II diabetes mellitus patients at Siti Fatimah Az-Zahra Hospital, South Sumatra Province. *Masker Medika*.

Wu, L., Wang, H., Liu, K., Zhao, L. & Xia, Y. 2024. Privacy and security trade-off in cyber-physical systems: An information theory-based framework. *International Journal of Robust and Nonlinear Control* 34: 5110–5125.

Yaqoob, I., Salah, K., Jayaraman, R. & Al-Hammadi, Y. 2021. Blockchain for healthcare data management: Opportunities, challenges and future recommendations. *Neural Computing and Applications* 34: 11475–11490.

Zhang, K., Zhou, H., Baptista-Hon, D., Gao, Y., Liu, X., Oermann, E., Xu, S., Jin, S., Zhang, J., Sun, Z., Yin, Y., Razmi, R., Loupy, A., Beck, S., Qu, J. & Wu, J. 2024. Concepts and applications of digital twins in healthcare and medicine. *Patterns* 5.

Zhang, Y., Qin, G., Aguilar, B., Rappaport, N., Yurkovich, J.T., Pflieger, L., Huang, S., Hood, L. & Shmulevich, I. 2024. A framework towards digital twins for type 2 diabetes. *Frontiers in Digital Health* 6:1336050. https://doi.org/10.3389/fdgth.2024.1336050.