

Article

OpenGluco—Innovative Open-Source Diabetes Care Management System

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Abstract

Continuous glucose monitoring (CGM) plays a central role in modern diabetes management, yet CGM data are often confined within proprietary manufacturer ecosystems, limiting interoperability and reuse. This paper presents OpenGluco, an open-source and provider-independent platform designed to unify CGM data from multiple commercial systems, including Abbott Freestyle Libre, Dexcom, and Medtronic. OpenGluco implements a modular server architecture that abstracts vendor-specific data access, normalizes heterogeneous glucose time series, and exposes standardized access through an application programming interface designed to support future scalability. The platform supports individual users as well as institutional and research deployments. Performance evaluation demonstrates reliable data ingestion, consistent API responsiveness within the evaluated deployment environment, and robust handling of heterogeneous sampling characteristics. Validation of data normalization shows preservation of clinically relevant metrics such as Time in Range. By emphasizing interoperability, user-authorized data access, and open-source transparency, OpenGluco provides a flexible foundation for clinical monitoring, education, and future analytics-driven decision-support applications in diabetes care.

Keywords: continuous glucose monitoring; interoperable health data; open-source health platform; Internet of Medical Things; diabetes management systems

1. Introduction

Over the past two decades, diabetes management has been fundamentally reshaped by the evolution of Continuous Glucose Monitoring (CGM) systems [1,2]. The transition from episodic capillary blood glucose testing to high-frequency continuous data streams represents a fundamental shift in the clinical paradigm of diabetes care [3,4]. Traditional finger-stick measurements provide sparse and context-limited snapshots, often failing to capture nocturnal hypoglycemia or rapid postprandial glucose excursions. In contrast, CGM systems address these informational voids by delivering near-real-time glucose values and trend information [4,5].

Advances in sensor accuracy, calibration strategies, and regulatory approval have transformed CGM from retrospective, professionally deployed tools into nonadjunctive, stand-alone medical devices approved for independent therapeutic decision-making without confirmatory capillary testing [3,5]. These developments have enabled detailed characterization of glycemic dynamics, variability, and rapid excursions, supporting more precise treatment adjustments and personalized diabetes management. Numerous clinical studies



Academic Editors: Brenda Scholtz and Hanlie Smuts

Received: 13 May 2026

Revised: 9 July 2026

Accepted: 10 July 2026

Published: 14 July 2026

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have demonstrated improved glycemic outcomes with CGM compared to conventional self-monitoring of blood glucose [6].

The influx of high-frequency CGM data has driven a parallel evolution in clinical interpretation practices. Standardized CGM-derived metrics—including Time in Range (TIR), Time Below Range (TBR), Time Above Range (TAR), and the Glucose Management Indicator (GMI)—are now recognized as more informative indicators of glycemic control and long-term complication risk than glycated hemoglobin (HbA1c) alone [4,5]. These metrics are commonly summarized using the Ambulatory Glucose Profile (AGP), a standardized 24-h visualization that supports shared decision-making between patients and clinicians [3,5].

Despite their clinical utility, most commercially deployed CGM systems operate within tightly integrated, vendor-specific ecosystems. Sensors and software platforms provided by Dexcom, Abbott (Freestyle Libre), and Medtronic employ proprietary data formats, communication protocols, and cloud infrastructures, limiting interoperability, portability, and third-party integration [7]. Even manufacturer-operated sharing platforms typically maintain centralized control over data processing and access, constraining transparency and user agency.

This fragmented landscape motivates the development of provider-independent CGM solutions capable of abstracting heterogeneous data streams while supporting standardized access and analysis. Such approaches offer the potential to mitigate vendor lock-in, enable cross-device comparability, and facilitate integration with emerging analytical, educational, and decision-support systems [8]. Against this backdrop, the present work introduces OpenGluco, an open and extensible platform designed to unify CGM data across providers and to promote interoperability, scalability, and user-authorized control within modern glucose monitoring ecosystems.

1.1. CGM Providers

The CGM market is currently dominated by a small number of major manufacturers, most notably Dexcom, Abbott (Freestyle Libre product line), and Medtronic. Each provider delivers a vertically integrated ecosystem comprising sensing hardware, data acquisition devices, and software platforms for glucose visualization and analysis. While the primary objective across these systems is continuous and reliable glucose monitoring, they differ considerably in hardware design, sensing modalities, communication technologies, data representations, application programming interfaces (APIs), and data-sharing capabilities.

Several open and vendor-independent CGM platforms have emerged to address limitations of proprietary ecosystems. Notable examples include Nightscout and Tidepool. Nightscout is a patient-driven, open-source platform that enables real-time CGM data visualization and sharing through a REST-based interface, and has been instrumental in advancing transparency and patient data ownership within the diabetes community. Tidepool provides a cloud-based, open-source infrastructure for aggregating and visualizing CGM and insulin pump data from multiple manufacturers and is widely adopted in both clinical and research contexts.

While these platforms demonstrate the feasibility and clinical utility of vendor-independent CGM data access, they primarily focus on end-user applications, reporting, or monolithic deployment models. In contrast, the goal of *OpenGluco* is not to replace existing platforms but to provide a modular, provider-agnostic middleware and data abstraction layer. This design emphasizes programmable access, institutional deployment, and seamless integration with external analytical tools, educational systems, and clinical decision-support frameworks.

From a technological perspective, Dexcom CGM systems, such as the G6 and G7, rely on Bluetooth Low Energy communication to provide continuous real-time glucose updates to mobile devices. Abbott's Freestyle Libre family has historically used near-field communication (NFC) scanning (Libre 1 and Libre 2), whereas newer generations, such as Libre 3, support continuous Bluetooth-based streaming. Medtronic CGM solutions are often tightly coupled with the company's insulin pump systems and depend on dedicated receivers and proprietary software, resulting in a highly closed and device-specific ecosystem.

In parallel with these established providers, newer CGM manufacturers are entering the market with increased emphasis on software-centric architectures and cloud-native data processing. Providers such as Syai exemplify this trend by prioritizing centralized data platforms, remote accessibility, and API-first integration strategies. Although these developments signal a gradual shift toward openness and scalability, the growing diversity of platforms continues to complicate cross-device integration and reinforces the need for standardized, provider-independent data access solutions.

1.2. Principles of Continuous Glucose Monitoring

Continuous Glucose Monitoring systems [1] are designed to provide near-real-time insight into glucose concentration dynamics by measuring glucose levels in the interstitial fluid rather than directly in capillary blood. Over the past decade, CGM technologies have become integral to diabetes mellitus management because of their ability to generate high-resolution temporal data and reveal glycemic patterns that are not observable using conventional self-monitoring techniques.

Most commercially available CGM devices rely on electrochemical biosensing principles. A miniaturized sensor is inserted into the subcutaneous tissue, where it interacts with interstitial fluid. The sensing element typically contains the enzyme glucose oxidase, which catalyzes the oxidation of glucose and produces an electrical signal proportional to the local glucose concentration. This signal is subsequently conditioned, digitized, and transmitted wirelessly to an external receiver or mobile application.

Wireless communication is commonly implemented using Bluetooth Low Energy or Near-Field Communication, depending on the device generation and manufacturer. Modern CGM systems typically operate with sampling intervals between one and five minutes, resulting in approximately 288 to 1440 measurements per day. This dense temporal sampling supports detailed characterization of glycemic dynamics, including detection of rapid excursions, assessment of glucose variability, and computation of clinically relevant metrics such as time-in-range.

A well-documented limitation of CGM technology is the physiological delay between blood glucose and interstitial glucose concentrations, generally reported to range from 5 to 15 min. This delay arises from diffusion and transport processes between vascular and interstitial compartments. While usually acceptable for long-term monitoring and trend analysis, this temporal offset must be considered in clinical interpretation and algorithmic decision-making, particularly during periods of rapid glycemic change.

From a systems integration standpoint, CGM devices exhibit significant heterogeneity in data accessibility and interoperability. Manufacturers commonly employ proprietary data formats, encryption schemes, and APIs, leading to variability in data granularity, update frequency, and integration capabilities. These challenges motivate the development of vendor-agnostic monitoring frameworks that abstract device-specific details while providing standardized and consistent access to glucose data streams.

1.3. Sharing Centers

To facilitate remote access to CGM data by patients, caregivers, and healthcare professionals, manufacturers typically deploy cloud-based data management platforms, commonly referred to as sharing centers. Prominent examples include Dexcom Clarity, Abbott LibreView, and Medtronic CareLink. These systems act as centralized repositories that collect, store, and process CGM measurements transmitted from end-user devices, offering visualization tools, summary analytics, and controlled data-sharing mechanisms.

Functionally, sharing centers provide longitudinal data storage, automated synchronization between sensors and cloud infrastructure, visualization of glucose trends, and generation of standardized clinical reports. However, their proprietary design introduces notable limitations, including strong coupling to specific devices, limited transparency of data processing workflows, restricted access to high-resolution or raw measurements, and constrained support for interoperable APIs.

These limitations reduce data portability for patients, complicate unified review across devices for healthcare providers, and hinder reproducible analysis and scalable integration for research and software development. Consequently, there is a clear need for provider-independent CGM data access frameworks that abstract vendor-specific characteristics while exposing standardized interfaces. Such frameworks aim to harmonize heterogeneous data sources, enable cross-platform interoperability, and support extensible clinical, analytical, and research-oriented applications, thereby forming the foundation of sustainable and open CGM data ecosystems.

2. Methods

The proposed solution consists of a provider-independent server application and a web-based client application that together form an integrated CGM data platform. The server application serves as a centralized backend responsible for interfacing with multiple CGM provider ecosystems, abstracting manufacturer-specific APIs, and delivering unified access to time-resolved glucose data. Its modular microservice architecture, combined with dedicated relational and time-series data stores, enables scalable data acquisition, normalization, and standardized API-based distribution to client applications and connected devices.

The web application builds upon this backend infrastructure to support structured visualization and analysis of CGM data. By relying on established clinical metrics and standardized data-processing methodologies, it ensures consistent interpretation and comparability of glucose measurements across heterogeneous CGM systems. Together, these components form an extensible and interoperable framework suitable for clinical use, research applications, and future system expansion.

2.1. Dependence on Manufacturer Cloud Services

Integration with commercial CGM systems is currently constrained by the access mechanisms provided by device manufacturers. OpenGluco retrieves glucose data exclusively through official or community-supported cloud services to which users have explicitly granted data-sharing authorization. This design reflects the prevailing regulatory and technical environment, in which direct device-level APIs are typically unavailable to third-party systems.

Reliance on manufacturer-operated sharing platforms, such as LibreLinkUp, Dexcom Share, and Medtronic CareLink, introduces inherent dependency risks, including undocumented API changes, access restrictions, or service discontinuation. To mitigate these risks, OpenGluco employs a modular provider interface design: each CGM integration is encapsulated within an independent component that can be modified, replaced, or disabled

without impacting the overall system architecture. Consequently, the unavailability of one provider does not affect data acquisition from others.

Although direct device-level access would better align with principles of patient data ownership and autonomy, such access remains limited by proprietary firmware, closed communication protocols, and regulatory constraints. OpenGluco therefore adopts a pragmatic integration strategy that operates within these limitations while explicitly advocating for more open and patient-centered CGM data access models.

2.2. System-Level Interpretation of CGM Integration

Each CGM provider ecosystem can be modeled as a distinct measurement channel characterized by vendor-specific sampling intervals, timestamp semantics, synchronization behavior, and latency. Formally, CGM measurements may be represented as a discrete-time observation process:

$$y_i(k) = h_i(x(t_k - \tau_i)) + v_i(k), \quad (1)$$

where $x(t)$ denotes the underlying physiological glucose concentration, $h_i(\cdot)$ represents the sensor- and provider-specific measurement mapping, τ_i is the effective transport and processing delay, and $v_i(k)$ captures measurement noise, quantization effects, and intermittent data loss.

The function of the OpenGluco platform is to abstract these heterogeneous characteristics into a unified, time-aligned representation. By normalizing timestamps, units, and sampling behavior, and by explicitly handling missing or delayed samples, the system produces observation streams that are suitable for downstream estimation, visualization, and control-oriented applications independently of vendor-specific constraints.

2.3. Data Normalization and Resampling

Raw CGM data streams are not directly comparable across devices due to differences in sampling frequency, timestamp definitions, update latency, and measurement units. OpenGluco therefore applies a standardized normalization pipeline that converts all glucose values to consistent units, transforms timestamps into ISO 8601 format in coordinated universal time (UTC), and aligns measurements to a unified internal schema.

When resampling is required, linear interpolation is applied only to short gaps in the data stream, while longer missing intervals are preserved and explicitly flagged. This approach prevents the introduction of artificial trends or biases while enabling consistent visualization and computation of clinically relevant summary metrics. The normalization strategy balances statistical comparability with preservation of clinically meaningful signal characteristics.

2.4. Server Application Topology

CGM data acquisition begins at the patient layer, where wearable sensors and associated mobile devices collect glucose measurements and synchronize them with manufacturer-operated cloud platforms. OpenGluco interfaces with these proprietary ecosystems through dedicated provider-specific download services (Dexcom, LibreLinkUp, and Medtronic), which handle authentication, authorization, and abstraction of vendor-dependent protocols.

Within the OpenGluco services layer, acquired data are processed and persisted using a dual-database strategy. A relational database is used for metadata storage, system configuration, user management, and access control, while a time-series database optimized for high-frequency measurements stores normalized glucose data. A unified REST interface exposes standardized CGM data to downstream consumers, including the OpenGluco web

portal, custom household devices, and institutional deployments. The complete data flow and component interactions are illustrated in Figure 1.

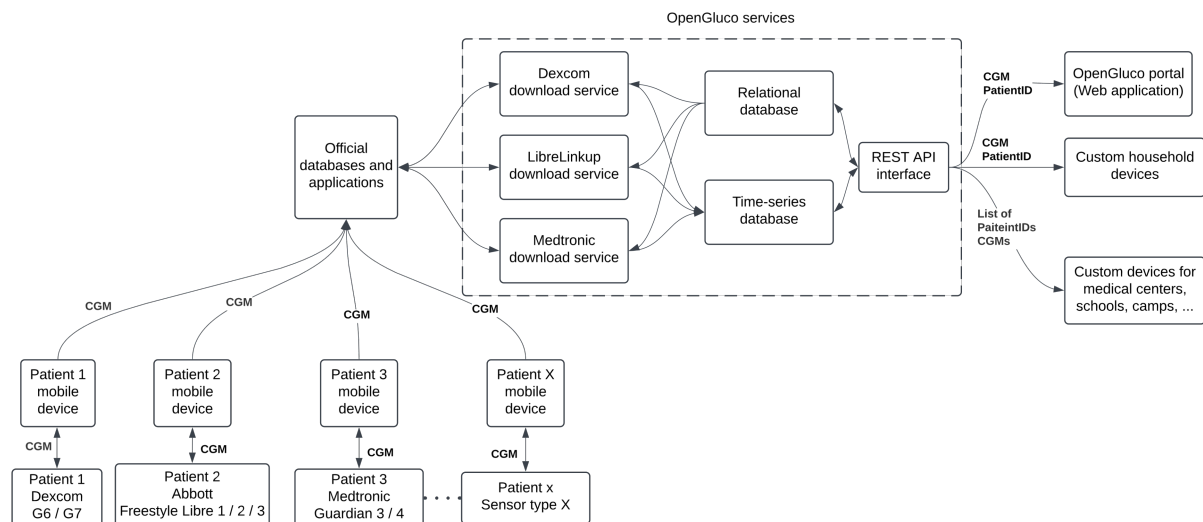


Figure 1. Topology of OpenGluko infrastructure.

2.5. Architecture Overview

The server application is designed as a modular, provider-agnostic system to ensure scalability, maintainability, and ease of extension. Provider-specific logic is decoupled from core system functionality, allowing individual CGM platforms to be integrated, updated, or replaced independently. The architecture comprises the following core components:

- **Provider microservices**—responsible for secure communication with specific CGM platforms, including authentication, data retrieval, and protocol adaptation.
- **Main server service**—coordinates inter-service communication, manages caching and access tokens, enforces the unified data model, and orchestrates data flow.
- **REST API**—exposing standardized glucose data and metadata to external applications, dashboards, and connected devices.

Data acquisition is implemented using community-maintained Python 3.14 libraries that interface with official manufacturer cloud services [9–11]. In parallel, several community-driven projects have demonstrated unofficial device-level CGM access using embedded platforms [12–14], illustrating both the feasibility and the demand for flexible and open integration approaches.

Supported Providers and Interfaces

The current implementation supports integration with three major CGM ecosystems using dedicated Python-based modules. Together, these manufacturers account for the majority of CGM devices deployed worldwide.

- **Abbott Freestyle Libre (LibreLinkUp):** Integration is achieved using the libre-linkup-py library [15], which interfaces with the LibreLinkUp cloud service. The module supports Libre 2 and Libre 3 sensors, manages access token renewal, and allows configuration of regional service endpoints.
- **Dexcom (Dexcom Share):** Dexcom systems are integrated using the Pydexcom library [10], which communicates with the Dexcom Share infrastructure. Data access requires a valid Dexcom account with sharing enabled and supports continuous data retrieval with built-in retry and token refresh mechanisms.
- **Medtronic (CareLink):** Medtronic CGM systems are accessed through community-developed wrappers for the CareLink API [11]. These devices are frequently integrated

with insulin pump systems and provide access to historical glucose data and pump-related status information. Due to platform constraints, real-time access is more limited than for Dexcom and Libre systems.

This modular strategy enables unified access to heterogeneous CGM sources while remaining extensible to additional manufacturers and interfaces.

2.6. Security and Privacy Considerations

The integration of distributed CGM systems into the IoMT expands the healthcare attack surface by transmitting sensitive physiological data across heterogeneous platforms [16,17]. This creates a resource-security paradox in which strong encryption competes with the limited energy and computational capacity of battery-powered sensors [17,18]. Additionally, the high value of medical data increases risks such as identity theft, requiring security strategies that address both technical and societal challenges [17,19]. Consequently, modern architectures are evolving toward decentralized, trust-aware, and intelligent security frameworks that protect privacy and safety throughout the data lifecycle [20,21].

Security and privacy are critical in interoperable healthcare systems, particularly in distributed CGM environments where sensitive patient data are exchanged across multiple platforms. The OpenGluco architecture addresses these requirements through authentication, secure communication, and data-integrity mechanisms while remaining compatible with heterogeneous healthcare ecosystems.

2.6.1. Authentication and Access Control

Authentication and access control in distributed healthcare increasingly leverage decentralized identity management and blockchain technologies to reduce single points of failure and improve patient control over medical identities [18,19]. Smart contracts can support granular permissions and mutual authentication, while RBAC and ABAC frameworks enable context-aware, fine-grained authorization [16–19]. These mechanisms help prevent unauthorized access and privilege-escalation attacks in cloud- and IoMT-based healthcare ecosystems [19,21].

Access to the OpenGluco platform is controlled through username–password authentication, with credentials validated by the server and authenticated sessions required for all operations. This ensures controlled access for patients, caregivers, and institutional users.

OpenGluco integrates with CGM providers through user-authorized cloud services such as Dexcom Share, LibreLinkUp, and CareLink. Rather than accessing devices directly, the platform retrieves data via authenticated provider sessions, delegating credential management and primary authentication to the respective providers and reducing the need to handle device-level credentials.

2.6.2. Secure Communication

Secure communication in IoMT environments relies on end-to-end encryption and protocols such as TLS to protect data exchanged between sensors, gateways, and cloud services [17]. While lightweight protocols like MQTT and CoAP improve efficiency, inadequate security can expose them to man-in-the-middle and session-hijacking attacks [17]. To address these risks, healthcare systems increasingly employ lightweight cryptography, physical layer security, secure routing, and intrusion detection mechanisms suitable for resource-constrained devices [17,19].

All data transfers within OpenGluco use encrypted HTTPS connections, protecting communications with both client applications and external CGM provider platforms from interception and man-in-the-middle attacks. This standards-based approach supports

secure cloud deployments and integration with institutional network infrastructures enforcing strict security policies.

2.6.3. Data Integrity and Validation

Data integrity is essential in CGM systems, where sensor spoofing or malicious data injection could compromise clinical decisions and automated insulin delivery [17]. Emerging approaches such as blockchain provide tamper-resistant audit trails, while homomorphic encryption enables analysis of encrypted data without exposing sensitive information [18,19,21]. Additionally, advanced validation techniques are needed to detect manipulated medical data and maintain the reliability of diagnostic evidence [17].

In OpenGluco, data integrity is primarily ensured by relying on manufacturer-operated cloud platforms as authoritative sources of CGM measurements. Because data are retrieved from provider ecosystems where they have already undergone processing and validation, measurement correctness and consistency are maintained at the source.

Additional integrity checks are performed during data ingestion and normalization, including timestamp validation, duplicate detection, and format verification. The absence of duplicate or out-of-order records in evaluation datasets indicates that these mechanisms effectively preserve data consistency across heterogeneous data sources.

2.6.4. Secure Interoperability in Distributed Environments

Secure interoperability in distributed healthcare relies on standardized communication frameworks that enable reliable data exchange across heterogeneous systems [20,21]. Technologies such as federated learning, middleware, and blockchain support privacy-preserving collaboration, policy enforcement, and regulatory compliance while maintaining scalability and resilience in growing IoMT ecosystems [16,18,19,21].

OpenGluco supports secure interoperability through a modular microservice architecture that isolates provider-specific communication within dedicated services. Each integration independently manages authentication, data retrieval, and protocol handling, reducing credential exposure and limiting the attack surface.

This design enables consistent security policies across heterogeneous CGM platforms while simplifying system extension and deployment. It also supports layered healthcare network architectures, where services can be distributed across protected zones to balance accessibility and data protection requirements.

2.6.5. Privacy and User Control

Privacy in digital diabetes care is challenged by continuous health-data collection, which may increase perceived surveillance and reduce user autonomy [20]. To address these concerns, healthcare systems increasingly adopt privacy-by-design principles, data de-identification techniques, and decentralized approaches that strengthen data sovereignty and regulatory compliance [16,20,21]. Transparent governance and user control are essential for maintaining trust and encouraging long-term engagement with digital health technologies [18,20].

OpenGluco employs a consent-based data access model in which information is retrieved only after explicit user authorization through provider sharing mechanisms. The platform also supports anonymization and pseudonymization strategies for research and institutional applications, enabling secondary data use while protecting user privacy.

Overall, the security architecture balances privacy, interoperability, and compatibility with existing CGM ecosystems, while providing a foundation for future enhancements such as stronger authentication and advanced data-protection mechanisms.

2.7. Implementation and Deployment

The OpenGluco platform is implemented as a modular backend system developed in Python, exposing a RESTful API and utilizing a dual-database architecture (relational and time-series storage). The system is designed to support both cloud-based and on-premise deployments, enabling flexible usage in personal, research, and institutional environments. A typical deployment consists of the core server, provider integration services, and database components.

For validation purposes, the system was deployed on Debian 12 Linux using a distributed configuration consisting of separate backend and web server instances. The backend server, hosting the OpenGluco API, provider integration services, PostgreSQL relational database, and InfluxDB time-series database, was provisioned with 2 vCPUs, 4 GiB RAM, and 62 GiB SSD storage. The web portal was deployed on a separate server with 2 vCPUs, 2 GiB RAM, and 8 GiB SSD storage. While OpenGluco is platform-independent and supports both cloud-based and on-premise installations, this reference configuration provides a reproducible deployment environment for the implementation described in this work.

Due to the diversity of deployment scenarios and the need to continuously adapt to changes in external CGM provider interfaces, detailed installation and configuration procedures are maintained outside the manuscript. Comprehensive and up-to-date deployment documentation, including setup instructions, integration guidelines, and community resources, is available through the official OpenGluco documentation portal and project website [22]. Although the OpenGluco portal is publicly accessible, some documentation, educational resources, and community features described in this manuscript are still under development and are planned for staged release following publication and further platform validation.

This approach ensures reproducibility while allowing the operational documentation to evolve independently of the publication.

2.8. Core CGM Metrics

The platform supports computation of standard statistical and clinical CGM metrics used in routine care and research, including:

- **Mean Glucose**—computed over configurable time windows;
- **Glucose Variability**—quantified using standard deviation (SD) and coefficient of variation (CV), with CV values above 36% considered clinically relevant;
- **Time in Range (TIR)**—defined as the proportion of time glucose values remain within a target range (typically 70–180 mg/dL) [2];
- **Time Above Range (TAR) and Time Below Range (TBR)**—reflecting hyperglycemic and hypoglycemic exposure.

These metrics form the foundation for therapy evaluation, clinical reporting, and personalized decision support.

Depending on the deployment context, CGM data may be aggregated temporally (e.g., daily or weekly summaries), analyzed across multiple users (e.g., family or clinical dashboards), or segmented by contextual metadata such as daytime versus nighttime or postprandial periods. The system architecture supports future extensions such as rule-based alerting, trend detection, and predictive modeling.

Visualization follows international CGM reporting recommendations and clinical best practices, including Ambulatory Glucose Profiles, daily overlays, heatmaps for temporal pattern recognition, and rate-of-change indicators. These visualization strategies are designed to enhance interpretability while preserving consistency across devices and providers.

3. Results

The OpenGluco project resulted in a fully functional, provider-independent CGM platform accompanied by a structured ecosystem of user-facing, developer-oriented, educational, and research-focused services. The achieved results can be grouped into four principal components:

- the OpenGluco server-side service,
- the OpenGluco patient portal,
- the OpenGluco API interface,
- and the OpenGluco support and documentation ecosystem.

3.1. Server-Side Service

The OpenGluco server-side service was successfully deployed as a provider-independent backend integrating multiple commercial CGM ecosystems. The service reliably retrieves glucose data from supported providers, applies normalization and synchronization pipelines, and stores the processed measurements in a unified internal data model.

In addition to raw glucose values, the backend computes standardized CGM metrics, including mean glucose, glucose variability, Time in Range (TIR), and Glucose Management Indicator (GMI). The server functions as the authoritative data source for all connected user interfaces and external integrations, demonstrating stable operation across heterogeneous provider data streams.

3.2. Patient Portal

A web-based patient portal was implemented to provide unified access to CGM data and derived metrics independently of the underlying device manufacturer. The portal enables visualization of real-time and historical glucose trends, assessment of aggregated clinical summaries, and longitudinal review of glycemic control.

The interface supports both individual self-monitoring and supervised access by caregivers or healthcare professionals, reflecting common clinical and domestic use cases. By abstracting vendor-specific presentation logic, the portal offers a consistent user experience across different CGM systems.

3.3. API Interface

The OpenGluco platform exposes a standardized RESTful API that provides access to normalized CGM measurements and computed clinical metrics. This interface enables automated and programmatic data access for third-party applications, custom devices, analytical pipelines, and research tools.

The API abstracts provider-specific data formats and synchronization behavior, allowing downstream consumers to interact with CGM data without dependence on proprietary vendor platforms. This capability supports extensibility and facilitates integration in both personal and institutional environments.

3.4. Support and Documentation Ecosystem

The OpenGluco platform is complemented by a set of dedicated support pages targeting different stakeholder groups:

- **Information pages**—describing project objectives, system architecture, and supported CGM providers;
- **Developer documentation**—including API references, integration guidelines, and architectural descriptions to support system extension;
- **Educational resources**—covering diabetes management concepts, CGM principles, and interpretation of clinical metrics;

- **Research materials**—outlining potential research applications enabled by standardized CGM data access, such as meal detection, algorithmic decision support, and embedded device development;
- **Community forum**—facilitating collaboration among users, developers, researchers, healthcare institutions, and international partners.

At the time of writing, some of the documentation resources, educational materials, and community-oriented features described above are still under development and are planned for staged public release following publication and further platform validation.

3.5. Platform Performance Evaluation

The performance of the OpenGluko platform was evaluated with respect to data ingestion latency, API responsiveness, scalability under concurrent access, and robustness of data handling. The evaluated deployment utilized a cloud-based infrastructure with a dual-database architecture comprising a time-series database for high-frequency CGM measurements and a relational database for metadata and access control. All measurements were obtained over a testing period of 45 days under controlled workload conditions.

3.5.1. Latency and Data Synchronization

End-to-end latency was defined as the elapsed time between data availability in the manufacturer cloud and successful ingestion into the OpenGluko time-series database. Observed latency ranged from 3 to 5 min (median: 4 min), with low variability within individual provider streams but systematic differences across providers due to their synchronization policies. Internal processing, including data normalization and storage, introduced minimal additional delay (median processing time 80 ms, 95th percentile 180 ms), confirming that the platform does not constitute a bottleneck in the ingestion pipeline.

Timestamp normalization ensured strictly consistent temporal ordering across providers, and no duplicate or out-of-order measurements were observed in the normalized data streams across 10 evaluated datasets. The observed data consistency error rate was 0%, demonstrating robust handling of heterogeneous and asynchronously updated input streams.

3.5.2. API Responsiveness and Limited-Concurrency Evaluation

API performance was evaluated under concurrent access by up to five simultaneous clients. Median response times remained stable at approximately 100 ms, with 95th percentile latency below 150 ms, indicating predictable and bounded response behavior under the evaluated workload. No significant increase in latency was observed within the tested concurrency range.

The system sustained a throughput of up to 120 requests per second without request failures or data inconsistencies. Resource utilization remained within acceptable limits during testing, and no degradation in data availability or correctness was detected.

These results demonstrate stable operation of the platform under the evaluated workload and confirm the suitability of the implementation for small-scale multi-user deployments. However, the present evaluation was not intended to determine the scalability limits of the platform under high-concurrency conditions.

A quantitative summary of the evaluated performance metrics under the tested workload conditions is provided in Table 1.

Table 1. Performance metrics obtained under the evaluated testing workload.

Metric	Median	95th Perc.	Description
End-to-end latency [min]	4	5	Provider synchronization delay
Processing time [ms]	80	180	Normalization and storage
API response time [ms]	100	150	Stable under load
Throughput [req/s]	120	–	Sustained maximum
Concurrent users	5	–	Tested workload
Data errors [%]	0	–	No duplicates or disorder

3.6. Validation of Data Normalization

To assess the impact of data normalization and resampling on clinically relevant metrics, CGM datasets were analyzed before and after normalization to a regular five-minute sampling interval. Metrics including mean glucose, coefficient of variation, and Time in Range were computed for both the original provider data and the normalized OpenGluco outputs.

Differences between original and normalized metrics remained consistently within clinically acceptable tolerance ranges, with mean absolute differences of approximately 2 mg/dL for mean glucose, 1.2% for coefficient of variation, and 1.5% for Time in Range. No systematic bias or directional shift was observed across evaluated datasets, and metric deviations exhibited low variance, indicating stable and reliable behavior of the normalization process.

These findings demonstrate that the normalization pipeline preserves both the statistical distribution and clinical interpretability of CGM data while enabling consistent cross-device comparability and standardized downstream analysis.

A quantitative comparison of clinical metrics before and after normalization is shown in Table 2.

Table 2. Impact of normalization on CGM-derived clinical metrics.

Metric	Original	Normalized	Difference
Mean glucose (mg/dL)	142	144	+2
Coefficient of variation (%)	32.5	33.7	+1.2
Time in Range (%)	71.0	72.5	+1.5

4. Discussion

The presented architecture and results position OpenGluco within the expanding ecosystem of Continuous Glucose Monitoring (CGM), Internet of Medical Things (IoMT), and automated insulin delivery (AID) technologies, where interoperability, data transparency, and user agency are increasingly critical. Open and vendor-independent platforms such as Nightscout and Tidepool have demonstrated the feasibility and clinical relevance of decoupling CGM data access from proprietary manufacturer ecosystems [23,24]. These initiatives have played a foundational role in advancing patient autonomy, data portability, and cross-device analysis in digital diabetes care.

OpenGluco adopts a complementary role within this ecosystem by focusing explicitly on middleware-level abstraction rather than end-user workflows or visualization. By separating device-specific data acquisition from normalization, storage, and downstream utilization, the platform supports programmable access, institutional deployment, and integration with external analytical and educational systems. This architectural approach builds on the principles of openness established by Nightscout and Tidepool while targeting scalable system integration rather than monolithic user-facing applications.

Table 3 provides a qualitative comparison of OpenGluco with existing solutions. A rigorous quantitative comparison of performance metrics such as latency, processing time, or resource consumption is currently difficult because many alternative platforms are proprietary systems whose internal architectures, deployment configurations, and operational characteristics are not publicly documented. In addition, OpenGluco was primarily designed to address interoperability, extensibility, deployment flexibility, and data ownership rather than optimization of computational performance. Future work will include systematic benchmarking of ingestion throughput, API response latency, and resource utilization across different deployment scenarios and hardware configurations.

Table 3. Comparison of OpenGluco with existing open-source CGM platforms.

Feature	OpenGluco	Nightscout	Tidepool
Primary focus	Middleware abstraction	Patient visualization	Clinical data platform
Architecture	Modular microservices	Monolithic web application	Centralized cloud platform
Extensibility	High (API-first, modular connectors)	Moderate (community extensions)	Moderate (controlled ecosystem)
Middleware abstraction	Strong (provider-agnostic layer)	Limited	Partial
API access	Standardized REST API	REST interface (less abstracted)	API with controlled access
Institutional deployment	Supported	Limited	Supported
Target users	Developers, researchers, institutions	Individual users, DIY community	Clinics, researchers

An additional limitation of the present study concerns performance evaluation. Testing was conducted using a workload of up to five concurrent users and was primarily intended to verify functional correctness, data consistency, and stable system operation. While the modular architecture supports deployment across multiple services and independent scaling of system components, the current results do not provide a comprehensive characterization of performance under institutional-scale workloads. Future work will therefore include controlled load-testing experiments involving substantially higher concurrency levels together with measurements of throughput, latency, resource utilization, and system behavior under peak load conditions.

While Nightscout and Tidepool have demonstrated the feasibility and clinical relevance of open CGM data access, their primary focus differs from the approach adopted in OpenGluco. Nightscout is oriented toward real-time visualization and patient-driven deployments, providing direct access to CGM data streams through a web-based interface. Tidepool, in contrast, represents a centralized platform for aggregation, visualization, and clinical use of diabetes-related data across multiple device types.

OpenGluco complements these approaches by focusing on middleware-level abstraction and programmable data access. By decoupling provider-specific integration from downstream applications, it enables a unified and extensible interface suitable for institutional deployment, research integration, and development of external analytical tools. This architectural distinction emphasizes flexibility, interoperability, and system-level integration rather than end-user application functionality.

Despite differences among CGM systems in sensing mechanisms, calibration, and noise characteristics, recent comparative studies report broadly comparable point accuracy across widely used devices [25]. This convergence supports the feasibility of provider-independent data processing and reinforces the value of unified analytical pipelines capable of aggregating heterogeneous CGM data streams. OpenGluco leverages this convergence

by enabling standardized normalization and metric computation across devices, facilitating reproducible analysis in both clinical and research contexts.

The increasing integration of CGM within IoMT ecosystems further highlights the importance of standardized and reliable data infrastructures. Artificial intelligence and machine learning techniques are increasingly applied to CGM data for denoising, short-term glucose prediction, and detection of unannounced factors such as physical activity, with reported detection accuracies up to 0.93 [4,26–28]. These analytical capabilities underpin modern AID systems, which couple continuous sensing to algorithm-driven insulin delivery, demonstrating improved glycemic outcomes while introducing additional technical and regulatory challenges [3,5,29].

As CGM systems become embedded within distributed IoMT infrastructures, security and systemic robustness emerge as critical concerns. The expanded attack surface of interconnected medical devices necessitates strategies for ensuring data integrity, confidentiality, and resilience against cyber threats [30,31]. Emerging solutions, including blockchain-based data provenance and Explainable AI (XAI), aim to enhance system transparency and trustworthiness, while also introducing additional design and governance considerations [18,31]. A vendor-independent and auditable data abstraction layer, as realized by OpenGluco, provides a principled foundation for implementing consistent security policies and reproducible processing pipelines.

Beyond technical performance, human-centered factors significantly influence adoption and long-term engagement with CGM and AID systems. Users of open-source AID systems report not only improved glycemic outcomes but also substantial emotional, social, and community-related impacts [32]. Furthermore, individual preferences, digital literacy, and perceived transparency play a decisive role in CGM system selection and sustained use [33]. These findings underscore that successful digital health platforms must balance technical robustness with usability and user autonomy—principles directly reflected in OpenGluco’s open and provider-agnostic design.

Looking ahead, CGM technology is progressing toward fully non-invasive sensing modalities based on alternative biological fluids such as sweat, tears, and saliva, aiming to further reduce user burden [3,4]. At the same time, wearable and nearable sensing platforms are beginning to extract digital biomarkers beyond glucose, enabling monitoring of cognitive, motor, and metabolic health within integrated digital ecosystems [4,34]. OpenGluco’s extensible architecture is well positioned to accommodate these future developments by providing a scalable and interoperable foundation for heterogeneous sensing technologies.

Overall, these trends emphasize that progress in diabetes technology depends not only on advances in sensors and algorithms, but also on the availability of interoperable, secure, and user-centered data infrastructures. OpenGluco contributes at this foundational level by enabling cross-device comparability, reproducible analysis, and flexible integration across the evolving CGM, IoMT, and AID landscape.

5. Conclusions

This work presented OpenGluco, an open-source and provider-independent platform designed to unify heterogeneous Continuous Glucose Monitoring data through a standardized measurement abstraction. The system integrates multiple vendor ecosystems, normalizes and synchronizes glucose measurements, and exposes them via a well-defined API designed to support scalable deployment and suitable for analytical, institutional, and research-oriented applications.

By addressing device heterogeneity and temporal synchronization, while employing architectural principles intended to support future scalability, OpenGluco establishes a robust foundation for system-level analysis, clinical reporting, and future decision-support

and closed-loop applications in diabetes care. The platform architecture, based on dedicated provider microservices for Abbott Freestyle Libre, Dexcom, and Medtronic, decouples vendor-specific data access from core processing logic. A central server component manages orchestration, normalization, access control, and persistence using a combination of relational and time-series databases, enabling efficient handling of both metadata and high-frequency glucose measurements.

Beyond end-user functionality, OpenGluco places strong emphasis on developer accessibility and extensibility. Through standardized APIs and modular provider interfaces, the platform enables researchers and developers to integrate additional sensors, analytical components, and decision-support tools without reliance on proprietary infrastructures. This openness supports innovation across clinical practice, education, and research while preserving user-authorized control and transparency over health data.

In summary, OpenGluco demonstrates that a provider-agnostic CGM platform is both technically feasible and practically valuable. By combining open-source principles, a microservice-based architecture, and standardized data handling, the platform provides an interoperable foundation designed to support future scalability through its modular architecture. Future work will focus on expanding provider support, enhancing real-time analytics and alerting, integrating predictive and control algorithms, and conducting formal scalability and load-testing evaluations alongside broader clinical and community-based deployments.

Author Contributions: Conceptualization, M.K., A.T., L.F. and M.C.; methodology, M.K. and A.T.; software, M.K. and L.F.; validation, A.T., L.F. and M.C.; formal analysis, A.T.; investigation, M.C.; resources, A.T. and M.C.; data curation, A.T.; writing—original draft preparation, M.K.; writing—review and editing, M.C.; visualization, L.F.; supervision, L.F.; project administration, L.F.; funding acquisition, L.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Tatra banka Foundation through the Digital for Universities grant program within the project Innovative Principles of IoT in Medicine and the subproject OpenGluco—Innovative IoT Applications in Medicine for Improving Diabetes Management. The provided funding was used for the acquisition of continuous glucose monitoring devices required for the development and experimental evaluation of the OpenGluco system presented in this study.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available on request to corresponding author.

Acknowledgments: During the preparation of this manuscript/study, the author(s) used GenAI for the purposes of formal corrections and text formatting. The authors have reviewed and edited the output and take full responsibility for the content of this publication. The authors would like to thank all participants who contributed to the experimental evaluation of the proposed system. The authors also acknowledge the diabetes clinics and healthcare professionals who provided valuable expert consultations and feedback during the development of the OpenGluco system, particularly regarding the requirements, functionality, and design considerations of the proposed solution.

Conflicts of Interest: The authors declare no conflicts of interest.

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