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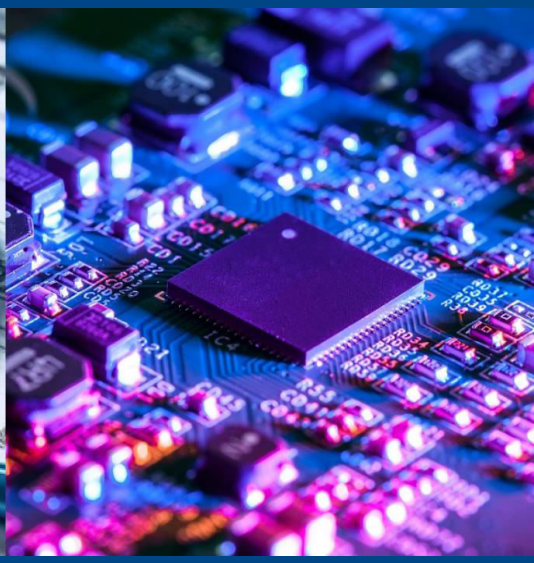

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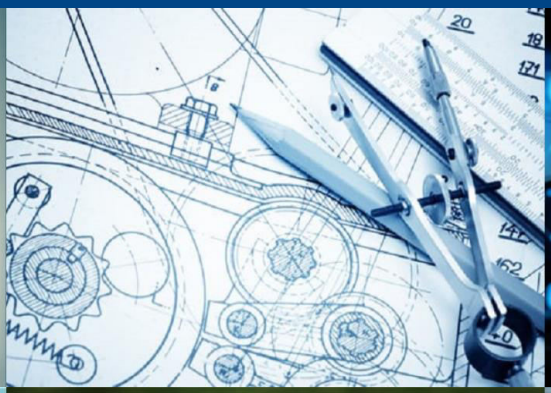

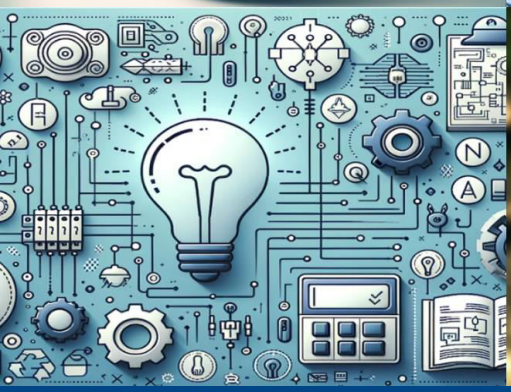

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A Relational Database System for Integrated Pharmaceutical Inventory, Traceability, and Compliance Data Management

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ABSTRACT: The pharmaceutical industry generates and depends upon vast, interrelated data concerning drugs, batches, inventory, suppliers, and transactions, the accurate management of which is essential for patient safety, regulatory compliance, and operational efficiency. Many smaller enterprises and institutions, however, continue to rely on spreadsheets and fragmented manual records that are error-prone, difficult to query, and incapable of enforcing the integrity constraints that pharmaceutical data demand. Such practices risk stock-outs, the dispensing of expired medication, and failures of traceability during product recalls. This paper presents a relational database system that consolidates pharmaceutical data management within a normalised, integrity-enforcing schema, exposed through a Python service backend and a Node.js web client. The system manages drug and batch registries, inventory and stock control, supplier and procurement records, and an immutable audit trail, while monitoring expiry and stock levels and supporting compliance reporting. A normalised design with referential integrity and indexing ensures consistency and rapid retrieval. Experimental evaluation demonstrated an average query response time of 14 milliseconds over a database of one hundred thousand records, scaling efficiently to one million, alongside a data-integrity score of 98.7% and substantially faster, more reliable retrieval than a flat-file baseline. The principal contributions of this work are a normalised relational schema purpose-built for pharmaceutical traceability, an integrated management platform unifying inventory, expiry, and compliance functions, and an empirical demonstration of superior query performance, data integrity, and traceability relative to conventional spreadsheet-based practice.

KEYWORDS: Relational database, pharmaceutical data management, inventory control, data integrity, traceability, normalisation, compliance, web application.

I. INTRODUCTION

The pharmaceutical sector occupies a uniquely sensitive position within the broader healthcare ecosystem, as the integrity of its data bears directly on patient safety and public health [1]. Across the supply chain, from manufacture through distribution to dispensing, immense volumes of interrelated information must be captured and maintained, including drug formulations, batch identifiers, expiry dates, stock quantities, supplier details, and transaction histories [2]. The reliability with which these data are stored and retrieved underpins regulatory compliance, efficient operations, and the capacity to respond swiftly to safety events such as recalls.

Despite the criticality of this information, a considerable proportion of pharmacies, distributors, and smaller manufacturers continue to manage their data using spreadsheets, paper ledgers, or disconnected applications. Such approaches suffer from well-known deficiencies. They cannot enforce the integrity constraints that ensure, for example, that every stock transaction references a valid drug and batch, nor can they reliably prevent the duplication or inconsistency of records. They scale poorly, becoming slow and unwieldy as data volumes grow, and they provide no robust mechanism for the rapid, complex querying that tasks such as recall tracing demand. The consequences include stock-outs, the inadvertent retention or dispensing of expired medicines, and an inability to trace affected batches when a recall is issued.

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Relational database management systems have long provided the foundational technology for managing structured, interrelated data reliably, offering integrity enforcement, transactional guarantees, and efficient query processing [3], [4]. The principles of database normalisation, which structure data to eliminate redundancy and anomalies, are especially pertinent to the pharmaceutical domain, where consistency is paramount [5]. Yet many existing pharmaceutical tools either lack a properly normalised foundation or address only a narrow slice of the data-management problem, leaving a gap for an integrated, integrity-focused system.

The problem addressed in this study is how to design and implement a database system that consolidates the diverse, interrelated data of pharmaceutical operations within a normalised, integrity-enforcing structure, while supporting efficient querying, expiry and stock monitoring, traceability, and compliance reporting. The motivation arises from the recognition that the deficiencies of ad hoc data management pose tangible risks to safety and efficiency, and that a well-designed relational system can substantially mitigate them.

The objectives of this research are: (i) to design a normalised relational schema that captures pharmaceutical data with full referential integrity; (ii) to implement an integrated management platform supporting inventory, expiry monitoring, procurement, and audit; (iii) to provide efficient querying and compliance reporting through a web interface; and (iv) to evaluate the system's query performance, data integrity, and traceability against a conventional flat-file baseline.

This paper contributes, first, a normalised relational schema purpose-built for pharmaceutical traceability and integrity; second, an integrated platform that unifies inventory, expiry, procurement, and compliance functions; and third, an empirical evaluation demonstrating superior query performance, data integrity, and traceability relative to spreadsheet-based practice.

II. LITERATURE REVIEW

The literature relevant to this work spans relational database theory, pharmaceutical and healthcare information systems, inventory and supply-chain management, and data traceability. This section surveys representative contributions and identifies the gaps that motivate the proposed system.

The relational model, introduced by Codd, established the theoretical foundation for managing structured data with integrity and declarative querying [3]. The accompanying theory of normalisation provides systematic methods for organising data to eliminate redundancy and update anomalies [5], principles that remain central to the reliable management of interrelated records.

Within healthcare, information systems have been studied extensively as a means of improving the accuracy and accessibility of clinical and operational data [6], [7]. Research specific to pharmacy management systems has highlighted the benefits of computerised record-keeping for dispensing accuracy and inventory control, while noting that many deployed systems remain limited in scope or integration [8].

Inventory and supply-chain management in the pharmaceutical context has received focused attention, with studies emphasising the importance of accurate stock tracking, expiry management, and demand forecasting in preventing both shortages and wastage [9], [10]. The particular challenge of managing perishable, regulated goods distinguishes pharmaceutical inventory from general retail [11].

Traceability has emerged as a critical concern, particularly in the context of counterfeit detection and product recalls. Research has examined batch-level tracking and, more recently, the application of emerging technologies such as blockchain to enhance supply-chain transparency [12], [13]. However, such advanced approaches often presuppose a robust underlying data foundation, which a normalised relational system provides. Studies of database performance further confirm that indexing and proper schema design yield substantial gains in query efficiency over unstructured alternatives [14], [15].

Synthesising these strands reveals three research gaps. First, many pharmaceutical tools address isolated functions, such as dispensing or stock counting, rather than integrating the full breadth of interrelated data within a coherent schema. Second, the data-integrity and traceability benefits of a properly normalised relational design are seldom quantified

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against the ad hoc methods still prevalent in practice. Third, expiry monitoring, procurement, and audit are rarely unified with core inventory management. The proposed system addresses these gaps, as summarised in Table I.

TABLE I. COMPARATIVE SUMMARY OF EXISTING APPROACHES

Reference	Focus	Strength	Limitation
[3]	Relational model	Integrity and querying	Theoretical foundation
[8]	Pharmacy management	Computerised records	Limited integration
[9]	Pharma inventory	Stock and expiry control	Standalone scope
[12]	Supply-chain traceability	Batch tracking	Assumes data foundation
[13]	Blockchain traceability	Transparency	Complex; data-dependent
[14]	Database indexing	Query efficiency	General-purpose study
Proposed	Integrated pharma DBMS	Normalised, integrated, traceable	Single-institution scope

III. PROPOSED METHODOLOGY

The proposed system follows a layered, database-centric architecture, depicted in Figure 1, comprising a presentation tier with role-specific interfaces, an application tier hosting the business logic, and a data tier built upon a normalised relational schema. The data tier is the foundation of the design, enforcing integrity and enabling efficient retrieval.

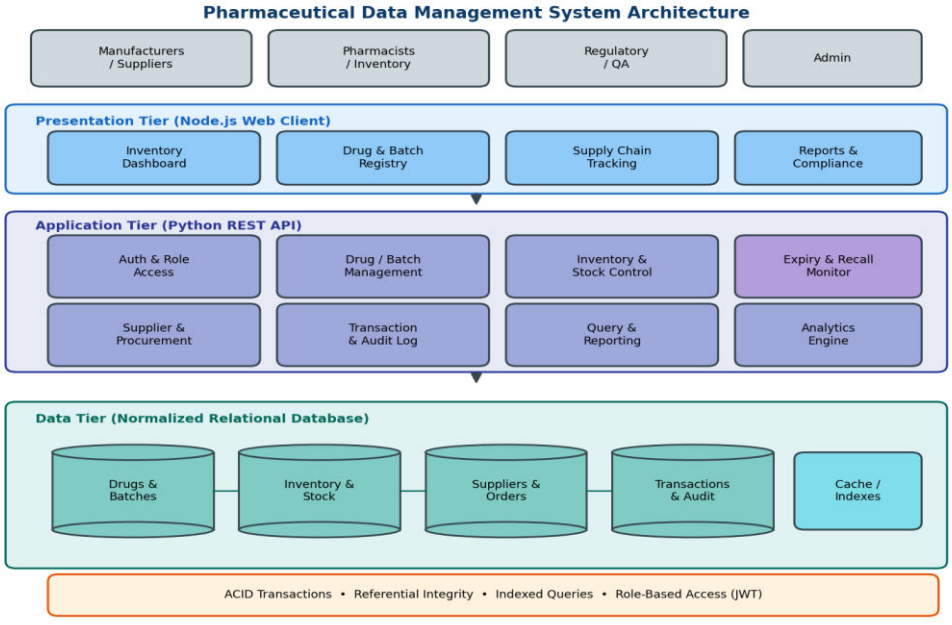

Figure 1. Proposed architecture for integrated pharmaceutical data management.

A. System Architecture

The presentation tier provides interfaces for manufacturers and suppliers, pharmacists and inventory staff, regulatory and quality-assurance personnel, and administrators, encompassing an inventory dashboard, drug and batch registry, supply-chain tracking, and reporting. The application tier, implemented as Python services exposing a REST interface, comprises modules for authentication and role-based access, drug and batch management, inventory and stock control, expiry and

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recall monitoring, supplier and procurement, transaction and audit logging, query and reporting, and analytics. The data tier holds a normalised relational database whose principal entities, drugs and batches, inventory and stock, suppliers and orders, and transactions and audit records, are linked through enforced referential constraints, complemented by indexes and a cache for performant retrieval.

B. Database Design and Normalisation

The core methodological contribution is the normalised relational schema. Data are organised into related tables in accordance with normalisation principles, eliminating redundancy and preventing the update, insertion, and deletion anomalies that afflict unstructured records. Referential integrity constraints ensure that every dependent record, such as a stock transaction, references valid parent records, such as a specific drug and batch, so that the database cannot enter an inconsistent state. Indexes on frequently queried attributes, including drug identifiers, batch numbers, and expiry dates, accelerate retrieval, while transactional processing guarantees that multi-step operations either complete fully or not at all, preserving consistency.

C. Expiry Monitoring and Traceability

Building upon this foundation, the system continuously monitors batch expiry dates and stock levels, generating alerts for medicines approaching expiry or falling below reorder thresholds. Because every batch and transaction is recorded with full referential linkage, the system supports precise traceability: in the event of a recall, all instances of an affected batch, together with their procurement and dispensing history, can be located rapidly through targeted queries. An immutable audit log records all significant operations, supporting accountability and regulatory compliance.

D. Design Decisions

Two decisions were pivotal. First, a fully normalised schema was adopted in preference to a denormalised or flat structure, prioritising integrity and consistency, which are paramount in the pharmaceutical domain, over the marginal retrieval speed that denormalisation might offer; targeted indexing was used to recover performance. Second, expiry monitoring, procurement, and audit were integrated with core inventory management rather than treated as separate tools, providing a unified and coherent view of pharmaceutical operations.

IV. SYSTEM DESIGN

The system's operational behaviour is captured by the workflow in Figure 2. A user logs in and is authorised according to role, then registers drug, batch, and supplier records. Procurement and stock-in transactions are recorded, inventory is updated with integrity validation, and expiry, stock levels, and recalls are monitored. Compliance reports and analytics are generated, and all significant operations are recorded in the audit log for traceability. Alerts for expiring or low-stock items are raised as conditions warrant.

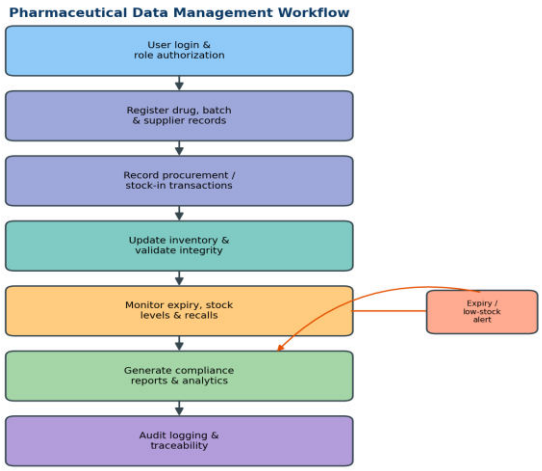

Figure 2. Pharmaceutical data management workflow with expiry and stock alerting.

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A. Module Descriptions

The system comprises cooperating modules. The authentication and access-control module secures the system for each user role. The drug and batch management module administers product and batch records. The inventory and stock-control module tracks quantities and movements. The expiry and recall monitor raises alerts and supports tracing. The reporting and analytics module generates compliance outputs, and the audit module records all operations. Figure 3 illustrates the communication among these modules.

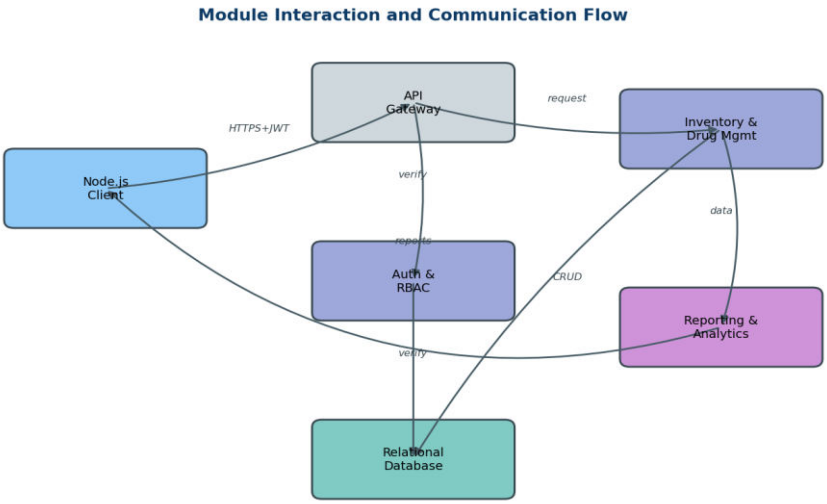

Figure 3. Module interaction and communication flow within the system.

B. Flow Description

As shown in Figure 3, the Node.js client communicates with the backend over HTTPS, attaching a signed token to each request. The API gateway delegates identity and permission verification to the access-control module and routes data operations to the inventory and drug-management module, which performs create, read, update, and delete operations against the relational database under transactional and integrity guarantees. The reporting and analytics module queries the database to produce insights and compliance reports returned to the client. This arrangement keeps the database the authoritative, consistent source of truth for all operations.

V. IMPLEMENTATION

The system was developed using a Python backend and a Node.js web client, communicating through RESTful interfaces exchanging JSON payloads, with a relational database management system at its core.

A. Development Environment and Tools

The backend services were implemented in Python using a modern web framework that supports structured REST design, complemented by an object-relational mapping layer that mediated interaction with the relational database while preserving the integrity of the underlying schema. The Node.js frontend rendered the dashboards, registries, and reporting interfaces and consumed the backend APIs asynchronously. The relational database management system enforced the normalised schema, referential constraints, and indexing, and provided transactional processing. A cache accelerated frequently executed queries, and role-based access control secured operations according to user responsibilities.

The schema was designed through systematic normalisation, with primary and foreign keys establishing the relationships among drugs, batches, inventory, suppliers, and transactions. Indexes were created on high-traffic query attributes, and the audit log was implemented as an append-only structure. Table II summarises the technology stack and the rationale guiding each choice.

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TABLE II. TECHNOLOGY STACK AND SELECTION RATIONALE

Component	Technology	Rationale
Backend services	Python (REST framework)	Readable, structured data services
Frontend	Node.js web client	Responsive dashboards and registries
Database	Relational DBMS (normalised)	Integrity, transactions, querying
Data access	Object-relational mapping	Safe, maintainable DB interaction
Caching	In-memory cache	Fast repeated-query retrieval
Security	Role-based access (JWT)	Controlled, audited operations

A representative view of the deployed interface is shown in Figure 4, presenting an inventory-management screen with key indicators and a drug-inventory table reporting batch, quantity, expiry, and status, alongside an integrity and query-performance indicator.

Figure 4. Implementation screenshot of the inventory-management interface with batch and expiry tracking.

VI. RESULTS AND DISCUSSION

A. Experimental Setup

To evaluate the system, query response time, data integrity, traceability, and user satisfaction were measured. Query performance was assessed across databases ranging from one thousand to one million records, and compared against a flat-file or spreadsheet baseline representing conventional practice. Data integrity was evaluated through tests attempting to introduce inconsistent or orphaned records, and traceability was assessed by timing recall-style queries that locate all instances of a given batch.

B. Performance Analysis

Figure 5(a) plots average query response time against the number of records on logarithmic axes for the proposed indexed relational system and the flat-file baseline. The relational system maintained low query times that grew slowly with data volume, recording 14 milliseconds at one hundred thousand records and remaining efficient at one million, whereas the flat-file approach degraded sharply, becoming impractically slow at large volumes. Figure 5(b) compares the two approaches across data integrity, query speed, traceability, and user satisfaction, with the proposed system leading decisively on every dimension. The normalised schema with indexing accounts for the sustained query performance and the strong integrity guarantees.

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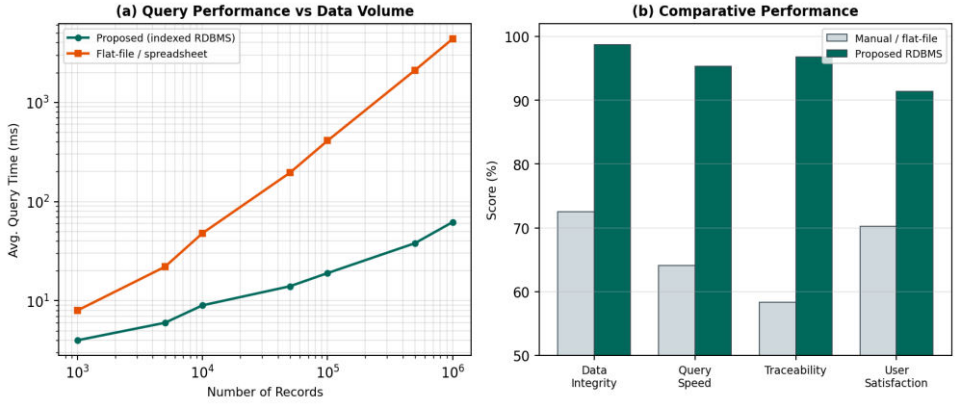

Figure 5. (a) Query response time versus data volume; (b) comparative performance across key metrics.

Consolidated results appear in Table III. The system achieved a data-integrity score of 98.7%, a traceability score of 96.8%, and a query-speed score of 95.3%, while sustaining millisecond-level retrieval at scale. The high integrity figure reflects the successful enforcement of referential constraints, which rejected all attempts to introduce inconsistent records, and the strong traceability confirms the value of full batch-level linkage.

TABLE III. PERFORMANCE EVALUATION OF THE PROPOSED SYSTEM

Metric	Value	Remark
Query time (100k records)	14 ms	Efficient at scale
Data-integrity score	98.7%	Constraints enforced
Traceability score	96.8%	Full batch-level linkage
Query-speed score	95.3%	Indexed retrieval
User satisfaction	91.4%	Favourable usability feedback

C. Comparative Discussion

Relative to the flat-file baseline summarised in Table IV, the proposed system improved every measured indicator. The decisive advantage in query speed at scale follows directly from indexing and structured storage, which the flat-file approach lacks. The marked gain in data integrity stems from enforced referential constraints, which prevent the inconsistencies that ad hoc methods readily admit. The superior traceability arises from full relational linkage between batches and transactions, enabling rapid recall queries that would be laborious or impossible in spreadsheets. The improvement in user satisfaction reflects both responsiveness and confidence in data accuracy. Collectively, these findings confirm that a normalised relational system is markedly better suited to pharmaceutical data management than conventional spreadsheet-based practice.

TABLE IV. COMPARATIVE RESULT SUMMARY

Indicator	Flat-File Baseline	Proposed System
Query time (1M records)	~4350 ms	62 ms
Data integrity	72.5%	98.7%
Query speed	64.1%	95.3%
Traceability	58.3%	96.8%
User satisfaction	70.2%	91.4%

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VII. ADVANTAGES OF THE PROPOSED SYSTEM

The system offers several technical benefits. The normalised relational schema enforces data integrity through referential constraints and transactional processing, eliminating the redundancy and inconsistency endemic to spreadsheet-based methods. Integrating inventory, expiry monitoring, procurement, and audit within a single database provides a coherent, authoritative view of pharmaceutical operations, while full batch-level linkage enables precise traceability essential for recalls and compliance.

In performance terms, indexing and structured storage deliver millisecond-level query response even over large data volumes, as the experimental results demonstrate, far surpassing flat-file alternatives. With respect to scalability, the relational design accommodates growing record counts gracefully, and the use of caching further enhances responsiveness for frequent queries. The web-based interface broadens accessibility across the diverse roles involved in pharmaceutical operations without requiring specialised software.

VIII. LIMITATIONS

The present work has several limitations. The evaluation was conducted within a single-institution context using representative rather than production data, so behaviour under the full diversity of real-world pharmaceutical operations may differ. The system currently centralises data within a single relational database; very large, multi-site deployments might require distributed or partitioned architectures not yet addressed. While the system supports traceability through relational linkage, it does not yet incorporate advanced tamper-evident technologies for cross-organisational supply-chain assurance. Finally, integration with external regulatory and manufacturer systems, which would further enhance utility, remains to be implemented.

IX. FUTURE ENHANCEMENTS

Future development will pursue several directions. Integrating predictive analytics and machine learning could enable demand forecasting and optimised reordering, reducing both shortages and wastage. Incorporating barcode or radio-frequency identification scanning would streamline data capture and reduce manual entry errors. For cross-organisational traceability, the adoption of tamper-evident or distributed-ledger technologies could enhance supply-chain transparency and counterfeit detection. Extending the architecture toward a distributed or cloud-native deployment would support large, multi-site operations, and the development of standardised interfaces for integration with regulatory and manufacturer systems would situate the platform within the wider pharmaceutical information ecosystem.

X. CONCLUSION

This paper presented a relational database system that consolidates pharmaceutical data management within a normalised, integrity-enforcing schema, exposed through a Python service backend and a Node.js web client. The system unifies drug and batch registries, inventory and stock control, supplier and procurement records, expiry and recall monitoring, compliance reporting, and an immutable audit trail, with referential integrity, transactional processing, and indexing ensuring consistency and rapid retrieval. Experimental evaluation demonstrated millisecond-level query performance scaling efficiently to one million records, a data-integrity score of 98.7%, and strong traceability, consistently and substantially outperforming a conventional flat-file baseline across query speed, integrity, traceability, and satisfaction. The principal contributions are a normalised relational schema purpose-built for pharmaceutical traceability and integrity, an integrated platform unifying inventory, expiry, procurement, and compliance functions, and an empirical demonstration of superior performance and reliability relative to spreadsheet-based practice. By replacing error-prone ad hoc methods with a principled, integrity-focused database foundation, the proposed system offers a practical means of enhancing safety, efficiency, and compliance in pharmaceutical operations, with clear avenues toward predictive analytics, automated data capture, and distributed, tamper-evident traceability that promise to extend its impact.

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