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Design and Implementation of an IoT-Based Quality Monitoring System for Sports Nutrition Production

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Abstract— Because nutritional formulations are sensitive to environmental and process variations, sports nutrition manufacturing requires stringent quality control mechanisms. Traditional quality as- surance approaches based on periodic inspections often lack real-time visibility, increasing the risk of undetected deviations. This study presents an IoT-enabled quality monitoring system designed for con- tinuous supervision of critical parameters such as temperature, humidity, and batch-level conditions. The proposed framework integrates distributed IoT sensor nodes, microcontroller-based data acquisition, and MQTT/HTTP communication protocols to enable reliable real-time monitoring in industrial environ- ments. Sensor data is integrated with a digital Quality Management System (QMS) infrastructure to support deviation detection, traceability, and automated compliance verification. PostgreSQL is employed for secure data storage, Flask-based services manage backend processing, and an Angular-based interface provides interactive dashboard visualization. Validation using simulated production and environmental datasets demonstrated a 37% reduction in non-conformance occurrences and a 50% improvement in data accessibility for quality evaluation. The results confirm that the proposed IoT architecture enhances proactive quality assurance in alignment with Industry 4.0 principles.

Keywords— *IoT, Quality Monitoring, Sports Nutrition Production, Digital QMS, Environmental Sen- sors, Industry 4.0.*

I. Introduction

Within the larger nutraceutical and food supplement sectors, the sports nutrition production industry is one of the fastest-growing. Protein powders, amino acid mixes, and functional energy formulas are in high demand due to the growing emphasis on fitness, individualized nutrition, and athletic performance throughout the world. Simultaneously, this expansion has raised concerns about product safety, quality, and regulatory compliance. In compliance with regulatory frameworks like the Food Safety and Standards Authority of India (FSSAI), ISO 22000, and Good Manufacturing Practices (GMP), manufacturers must make sure that every stage of production—from sourcing and formulating raw materials to packaging and storage—is continuously monitored, documented, and traceable.

In sports nutrition production, traditional Quality Management Systems (QMS) are mostly paper- based or rely on dispersed digital instruments that function independently without centralized data integration. Because quality records, test reports, deviation logs, and supplier verification documentation are frequently kept in disparate forms, retrieval during audits is ineffective and prone to mistake. More importantly, these systems are unable to continually monitor process and environmental factors that have a direct impact on product quality. The stability of bioactive components, such as branched-chain amino acids (BCAAs), electrolytes, and plant-derived extracts, can be negatively impacted by temperature and humidity variations during crucial processes such ingredient mixing, drying, or storage. Deviations may go unnoticed until post-production inspection stages in the absence of real-time monitoring and automatic alarm systems, raising the possibility of non-conformance issues. [1].

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By facilitating automated data collection, data-driven decision support, and ongoing quality monitoring, a digital quality management system goes beyond traditional document digitalization. Distributed sensor networks may be used to record environmental and operational characteristics in real time when Internet of Things (IoT) technologies are integrated into quality management frameworks. IoT-enabled sensors can continually monitor temperature, humidity, and batch-specific parameters across several production stages in the sports nutrition manufacturing industry. Instead than depending just on sporadic inspections, this sensor-driven method provides proactive quality control by identifying deviations as they happen. These solutions are in line with Industry 4.0, which combines analytics, connectivity, and cyber-physical systems to create intelligent industrial environments. [2].

Regulatory paperwork and audit readiness are two more enduring issues in sports nutrition production. Standard Operating Procedures (SOPs), batch production records, corrective and preventative action (CAPA) reports, and validation documentation must all be strictly controlled in order to comply with FSSAI and ISO 22000. Version discrepancies, delayed approvals, and poor traceability are frequently the results of manual document management. Time-stamped records that are directly connected to sensor data, role-based access, and automatic document version control are all introduced by a digital QMS that is integrated with IoT-based monitoring. This connection maintains consistency between defined processes and real production circumstances while increasing transparency, lowering administrative complexity, and ensuring ongoing audit preparedness. The utilization of imported raw materials, specialized protein isolates, and botanical extracts that have to adhere to stringent purity and contamination standards make ingredient tracing more difficult. It becomes difficult to manage batch usage, testing history, and ingredient provenance without a centralized digital infrastructure. In order to overcome this difficulty, the suggested digital QMS uses unique identities connected to real-time monitoring data to achieve batch- level traceability. A thorough digital chain of custody is created by linking each production batch to environmental monitoring logs, supplier verification documents, and ingredient quality certificates. This feature increases operational resilience and customer trust by enabling quick root-cause analysis and targeted product recalls when needed. [3]. From an electrical and electronics engineering perspective, IoT-based quality monitoring relies on sensor interfacing circuits, embedded microcontroller units, and wireless communication modules. Industrial IoT deployments commonly use lightweight protocols such as MQTT and HTTP for low-latency data transmission. Proper sensor calibration, signal conditioning, and reliable electronic integration are critical to ensure measurement accuracy and system stability in production environments.

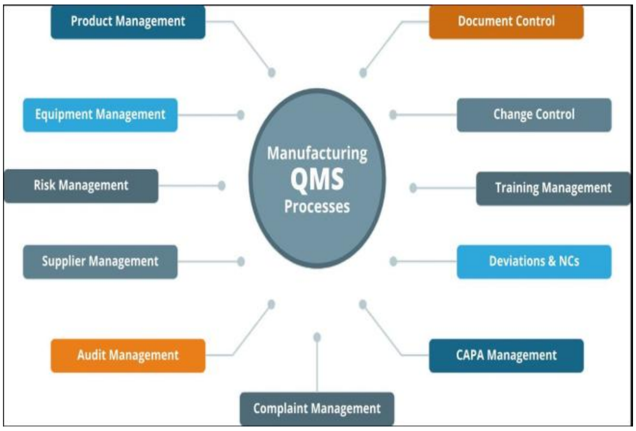


Fig. 1: IoT-enabled quality monitoring architecture

Data-driven quality management is made easier by integrating IoT-enabled monitoring into a digital QMS, which goes beyond compliance assurance. Recurring deviations, process inefficiencies, and environ- mental instability patterns can be identified by ongoing data collecting. Key quality indicators including batch performance summaries, environmental stability measures, and deviation frequency may be shown in real time using visualization dashboards. By detecting possible hazards before they affect product quality, these insights facilitate predictive quality management and promote continuous improvement activities [4].

The goal of this project is to create, develop, and verify a digital QMS infrastructure-supported IoT- enabled quality monitoring system for sports nutrition production. To provide ongoing quality control, the suggested system uses a modular design that integrates web-based apps, IoT sensors, and centralized data storage. PostgreSQL facilitates safe data storage and traceability, Angular is utilized for the frontend interface, and Python (Flask) is employed to create the backend. System performance, responsiveness, and usability are assessed using simulated datasets that reflect production batches and environmental sen- sor streams. Improvements in operational responsiveness, traceability, and quality monitoring efficiency are evident as compared to traditional manual procedures.[5].

By addressing the unique needs of sports nutrition production, our study adds to the growing body of literature on IoT-enabled quality monitoring in nutraceutical manufacturing. Prior studies have exam- ined IoT adoption in the food processing and pharmaceutical industries, but sports nutrition production, which requires strict quality control under resource-constrained settings, has received less attention. The suggested framework offers a scalable and industry-relevant solution that improves sustainable competi- tiveness, regulatory harmonization, and real-time quality assurance.

II. Literature Review

According to research, Quality Management Systems (QMS) are essential for guaranteeing process uni- formity, product safety, and regulatory compliance in food and nutraceutical production settings [6]. Strict control over quality standards is essential in the sports nutrition industry, as formulations fre- quently comprise sensitive bioactive substances and performance-oriented components. To guarantee batch-level compliance, established standards like ISO 22000 and Good Manufacturing Practices (GMP) offer systematic documentation and accountability procedures. Nevertheless, many firms still use manual or semi-digital workflows despite their acknowledged significance, which leads to fragmented data man- agement, redundant paperwork, and poor traceability. These inefficiencies often result in variable quality outputs, higher compliance costs, and delayed remedial measures.

Recent scientometric and platform-level studies further highlight trends and architectures useful for quality monitoring systems. Axiotidis et al. describe a wireless sensor-network IoT platform for dis- tributed environmental monitoring (consumption and quality monitoring), demonstrating practical long- range communications, multi-sensor interfacing and mobile/desktop UI components for remote super- vision [7]. A mapping review of IoT applications in industrial management by Mu et al. identifies mainstream topics such as digital twins, edge computing, and interoperability as central to current re- search directions [8]. Work on industrial sensor networks and cloud analytics also shows that combining local edge analytics with cloud storage/visualization enhances both anomaly detection and predictive maintenance use cases [9, 10].

Recent studies have emphasized the role of edge-assisted IIoT architectures for improving the time- liness and robustness of industrial monitoring. Mirani et al. present an IIoT deployment that performs data processing at the edge to compute additional analytical energy parameters and provide local dash- boards for factory-floor monitoring, demonstrating how edge enrichment reduces cloud traffic and im- proves responsiveness in energy-sensitive industrial applications [11]. Similarly, Wang et al. combined IIoT, OPC-UA digital twin models, and reinforcement-learning based automation to achieve real-time production monitoring and automated process transformation in smart manufacturing, showing clear benefits in production efficiency and end-to-end system automation [12].

Research further shows that during regulatory audits, standard QMS systems are unable to provide transparency, accurate data, and prompt decision-making [13]. Data loss and inconsistency are more likely when batch production records, deviation reports, and calibration logs are kept in physical registers or spreadsheet-based systems. By facilitating centralized record repositories, automatic timestamping, and document version control, digital QMS solutions overcome these constraints. According to research, combining deviation monitoring with root-cause analysis modules speeds up corrective and preventative actions (CAPA), which improves operational responsibility and audit preparedness.

The research now in publication highlights the use of risk-based quality management techniques in food manufacturing that are in line with Hazard Analysis and Critical Control Point (HACCP) principles [14]. By linking quality control data to crucial process factors like moisture content, mixing time, and microbiological thresholds, digital systems provide dynamic risk assessment. This proactive strategy lessens reliance on manual monitoring while improving formulation uniformity and contamination control in sports nutrition production. Continuous improvement activities are supported by automated alarm mechanisms that guarantee prompt response when deviations surpass certain levels.

One of the most resource-intensive aspects of implementing a QMS is still managing regulatory doc- uments. According to research, typical document handling procedures frequently lead to audit risks and version discrepancies. Centralized repositories with role-based access control, automated review pro- cedures, and compliance-aligned preservation methods are introduced by digital QMS solutions. These features greatly lower documentation-related non-conformance problems for manufacturers working under standards like FSSAI and ISO 22000 while enhancing accountability and transparency.

Beyond compliance, research indicates that by guaranteeing consistent product performance and ver- ifiable traceability, well-executed QMS frameworks boost market competitiveness and brand credibility [15]. Digital quality systems function as both regulatory protections and brand assurance methods in the sports nutrition industry, where customer trust is strongly linked to product authenticity and safety claims. Furthermore, maintaining uniform quality standards is made more difficult by hybrid production methods that involve contract partners. Cross-organizational traceability and supplier verification are strengthened by digital platforms that provide synchronized quality data exchange between facilities and suppliers [3].

The increasing integration of Internet of Things (IoT) technology inside manufacturing quality sys- tems is highlighted by recent developments in industrial digital transformation [1]. IoT-enabled sensors reduce the need for sporadic human inspections by enabling continuous monitoring of process and envi- ronmental parameters. Real-time monitoring facilitates the early detection of deviations and supports preventative quality control techniques in sports nutrition manufacturing environments where temperature and humidity immediately affect powder stability and ingredient integrity.

Further research shows that by connecting sensor-generated data with production records, IoT- enhanced digital QMS platforms offer end-to-end batch traceability [4]. Real-time dashboards and auto- mated notifications drastically cut down on response times to deviations, reducing downtime and averting batch rejections. Digital twin integration has also drawn interest as a way to use virtual simulation to optimize manufacturing quality . Organizations may assess process modifications without interfering with physical operations by digitally modeling industrial processes. This improves formulation uniformity and environmental control tactics.

Scalable and centralized quality management architectures have been shown to be made possible by cloud computing . Cloud-based technologies facilitate remote accessibility and uniform quality control by providing real-time synchronization across geographically dispersed facilities. Additionally, by anticipating deviations and equipment abnormalities before they happen, predictive analytics based on historical process data improves the intelligence of digital QMS frameworks . Such predictive skills aid in maintaining batch homogeneity, cutting down on material waste, and increasing operational efficiency in the sports nutrition production industry.

Additionally acknowledged as crucial elements impacting the efficacy of digital quality systems are user-centric visualization and real-time reporting [2]. Operators and management may make quicker and more informed decisions by effectively interpreting complicated data streams thanks to intuitive dashboards. However, cybersecurity is still a major issue for IoT-enabled quality systems. To safeguard critical quality data and guarantee regulatory compliance, research highlights the necessity of secure authentication methods, encrypted communication protocols, and multi-layered access control .

Despite these developments, there are still a number of gaps in the literature and areas for further study. Many digital QMS implementations are still generic and inadequately adapted to the unique operational and regulatory problems of the manufacture of sports nutrition [5]. Furthermore, the shift from reactive quality control to proactive quality assurance is hampered by the underutilization of IoT data for predictive quality analytics. Digital QMS adoption is often seen by small and medium-sized businesses (SMEs) in the sports nutrition sector as expensive and technically challenging, underscoring the need for modular, open-source solutions based on accessible technology . Lastly, conceptual digital quality frameworks and verified real-world implementations continue to diverge, highlighting the significance of empirical research that develops, prototypes, and assesses fully operational IoT-enabled quality monitoring systems. Several recent works in the field of electrical and electronics engineering have applied IoT architectures for industrial parameter monitoring and quality assessment. Prabhakara Rao et al. proposed a wireless sensor network architecture integrating IoT nodes with real-time data acquisition to monitor industrial faults and operational conditions . Their system demonstrated lower latency and higher reliability in data delivery, highlighting the benefits of distributed sensor deployments in industrial environments. Such IoT frameworks are closely aligned with the goals of quality monitoring systems in modern production processes.

The integration of IoT technologies with automated testing and control systems has also been explored in recent SSRG IJEEE publications. Salcedo et al. developed an automated testing system for alternators using IoT and electrical data analysis to facilitate real-time diagnostic monitoring and reporting . Similarly, Cairo et al. implemented intelligent IoT control for rectifiers and pneumatic valves, optimizing industrial processes such as chrome plating and pickling operations . These studies reflect the trend of utilizing sensor-enabled electronic control systems to enhance both automation and quality assurance in industrial applications. Further research in wireless IoT monitoring has demonstrated the value of bidirectional communication and safety automation in industrial contexts. Cornejo et al. presented a control system with bidirectional IoT communication that enables remote monitoring and feedback control over embedded devices, improving system responsiveness and adaptability . Earlier foundational work by Majee applied IoT automation for safety and monitoring in mining operations, showing the applicability of IoT systems for hazard detection and environmental sensing . These contributions reinforce the impor- tance of combining wireless sensor systems, embedded control, and real-time data analytics in the design of industrial quality monitoring frameworks.

III. Methodology

In order to build and verify an IoT-enabled quality monitoring framework backed by a digital Quality Management System (QMS) for sports nutrition production, this project used an organized build Science Research (DSR) methodology. Four successive steps comprised the study framework: (1) requirement identification; (2) system architecture design; (3) workflow and data flow modeling; and (4) prototype implementation and validation. Every level builds on the results of the one before it, guaranteeing prac- tical application, regulatory alignment, and technical robustness. The method addresses operational and compliance-driven quality issues by combining the concepts of systems engineering, quality management, and iterative software development.

Analyzing current manual and semi-digital quality workflows utilized in sports nutrition production facilities was the main goal of the first phase. Redundancies, data fragmentation, and bottlenecks impact- ing batch traceability, audit readiness, and real-time quality visibility were found using process mapping methodologies. The functional scope of the suggested system, which includes batch-level traceability, document lifecycle management, deviation tracking, and continuous IoT-based environmental parameter monitoring, was guided by these insights. To guarantee compliance with food safety and quality standards, regulatory requirements required by FSSAI, ISO 22000, and GMP were included into the design limitations.

By converting specified needs into modular system components that could handle both static quality records and dynamic sensor data, the study advanced. To guarantee that the framework allows ongoing quality monitoring while upholding the integrity of regulatory documents, a mixed-methods approach integrating qualitative process analysis and quantitative data modeling was used. Instead of depending solely on post-process inspection, the resultant system places an emphasis on proactive quality control through real-time data capture.

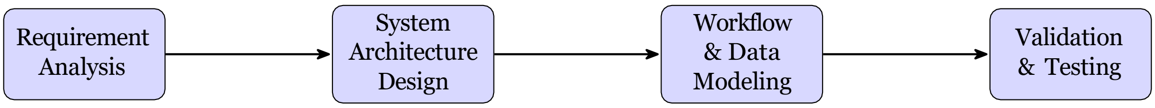


Fig. 2: Research framework illustrating the sequential development and validation stages

0.1 Requirement Analysis and System Specification

The basis for creating an IoT-enabled quality monitoring system that can satisfy operational and regulatory requirements was laid during the requirement analysis phase. To guarantee balanced system performance, requirements were divided into functional and non-functional categories. The framework's operational capabilities, such as document control, CAPA tracking, batch traceability, audit management, supplier quality monitoring, and real-time environmental sensing, were specified by functional requirements. System characteristics including scalability, data security, performance efficiency, usability, and compatibility with current corporate systems were all covered by non-functional criteria.

Each manufacturing batch was given a unique digital identification that connected quality documentation, process records, and IoT sensor data in order to guarantee traceability and regulatory compliance. Workflows connected to quality, from the input of raw materials to the release of the finished product, were modeled using Business Process Model and Notation (BPMN) diagrams. Decision points, approval hierarchies, and exception management techniques like batch rejection and deviation escalation were all represented by these models. Database schema design, application logic, and user interface development were all informed by the finished requirement document.

0.2 System Architecture and Data Flow Modeling

With an emphasis on flexibility, interoperability, and safe data flow, the suggested system architecture was created as a four-layer IoT-enabled digital ecosystem. Workflow approvals, document management, and real-time display of quality indicators are all made possible by the presentation layer's web-based Angular interface. The application layer oversees workflow orchestration, API services, and business logic and is developed with Python (Flask). To preserve data integrity across quality records, sensor logs, and audit trails, the database layer uses PostgreSQL with a normalized schema. As the data intake method, the IoT integration layer records real-time environmental data from industrial settings, including temperature, humidity, and equipment vibration.

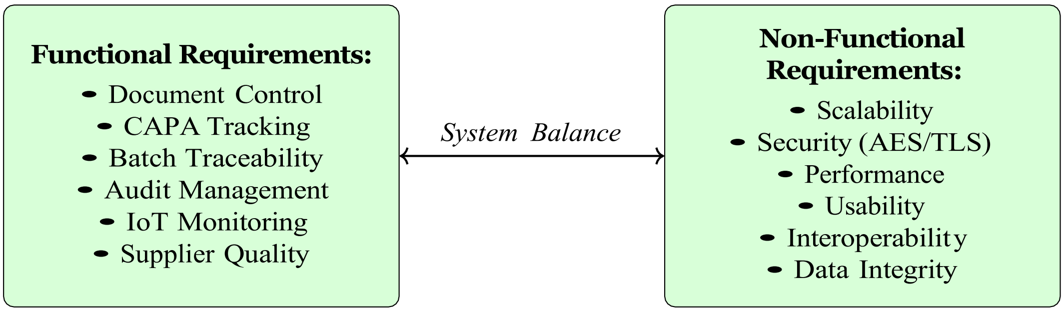


Fig. 3: Functional and non-functional requirement mapping

While MQTT or HTTP protocols are used for IoT data transfer, RESTful architecture is used for communication between levels. When sensor data reaches the application layer, it is verified and time- stamped before being entered into structured database tables. Compliance with data protection regulations is ensured by security measures including role-based access control, TLS for data in transit, and AES-256 encryption for data at rest. Future integration of predictive quality modules or sophisticated analytics is possible because to the loosely linked architecture, which doesn't interfere with essential system operations.

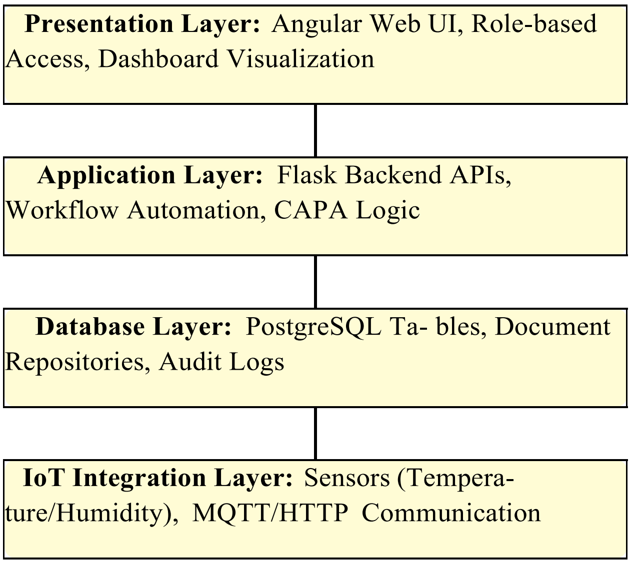


Fig. 4: Layered architecture of the IoT-enabled quality monitoring framework

0.3 Prototype Development and Validation

Validating the suggested framework under simulated production settings was the main goal of the prototype implementation phase. An Angular-based UI offered real-time visualization and user interaction, while a Flask-based backend was created to manage quality records, deviation workflows, and CAPA procedures. Synthetic datasets that represented manufacturing batches, raw material lots, environmental sensor readings, and non-conformance records were added to the PostgreSQL database. Repeatability and adherence to data confidentiality regulations were guaranteed via synthetic data.

Microcontroller-based sources that periodically sent temperature and humidity values were used to replicate IoT data streams. The system received these data, stored it in time-series tables, and used interactive dashboards to display it. Functional testing, performance evaluation, and usability assessment were the components of validation. Usability testing evaluated user engagement with dashboards and approval processes, performance testing measured latency and data retrieval efficiency, and functional testing confirmed the execution of quality operations.

The validation findings showed better reactivity to quality deviations, decreased document retrieval time, and improved batch traceability. A quantifiable decrease in process delays and human interaction was seen as compared to manual operations. With potential for future improvement through predictive analytics and intelligent decision-support modules, the prototype validates the viability of using the suggested IoT-enabled quality monitoring framework in sports nutrition industrial contexts.

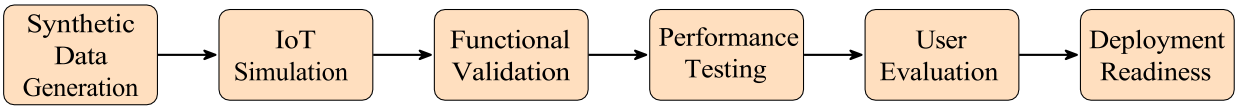


Fig. 5: Prototype validation and testing workflow

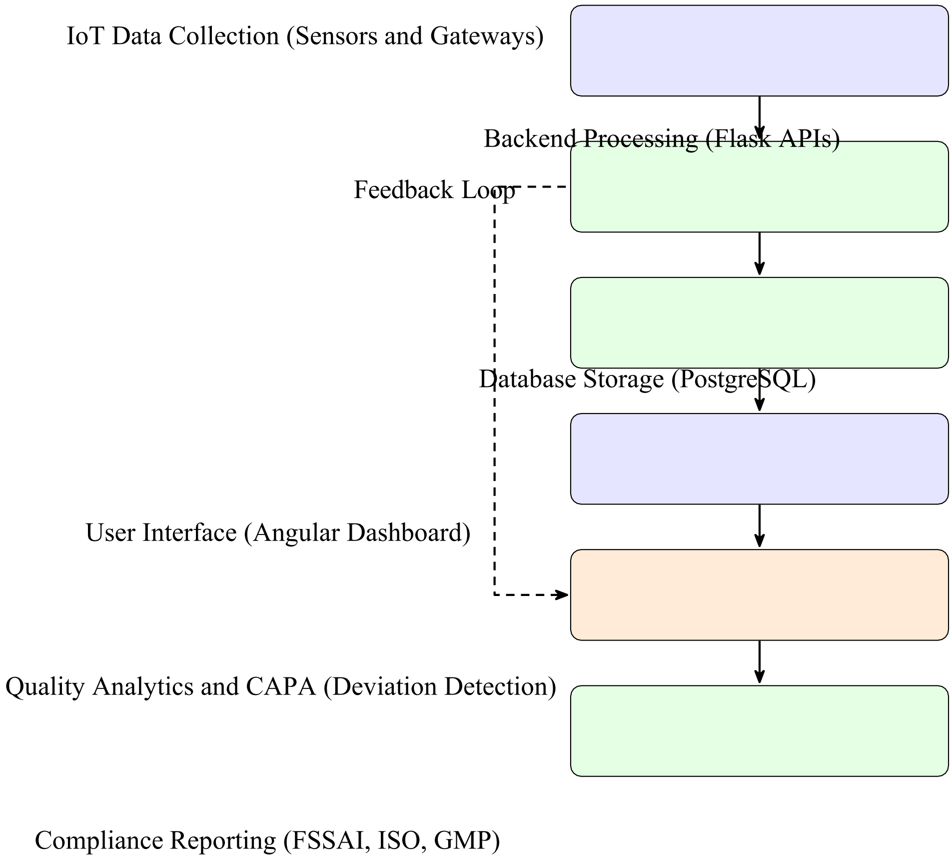


Fig. 6: Integrated IoT-enabled digital quality monitoring workflow

Although simulated datasets were used for validation due to limited access to real industrial produc- tion data and regulatory constraints, the simulation parameters were designed to closely replicate real production environment

IV. System Implementation

0.4 System Development Overview

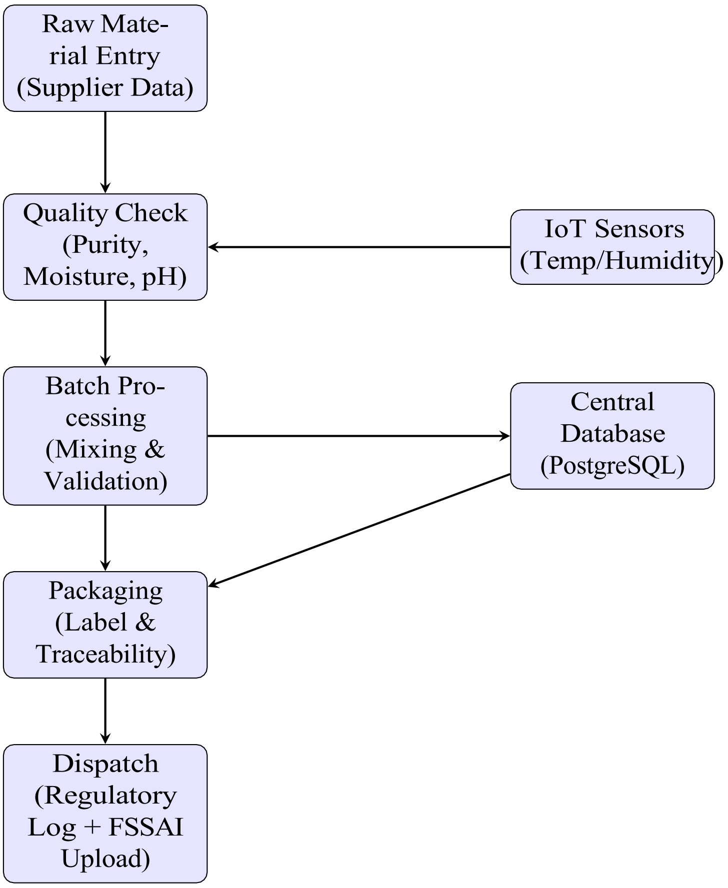


Fig. 7: System flow diagram of the IoT-enabled quality monitoring framework

In order to provide ongoing quality assurance, environmental stability, and regulatory compliance in sports nutrition production, the implementation focuses on implementing an IoT-enabled quality monitoring system backed by a digital Quality Management System (QMS). The system was created using a modular design, utilizing PostgreSQL for centralized data storage, Python (Flask) for backend services, and an Angular-based dashboard for user interaction and real-time visualization. This design maintains flexibility for future additions while enabling the smooth integration of IoT sensor streams, batch-level quality data, and regulatory documents inside a single platform.

Raw material input is the first step in the system workflow, which then moves on to quality evaluation, batch processing, packing, and delivery. Critical quality parameters, including ingredient purity, moisture content, and pH, are compared to predetermined thresholds in accordance with FSSAI, ISO 22000, and GMP regulations at each stage using automated validation criteria. Temperature and humidity sensors with Internet of Things capabilities offer constant environmental monitoring in production and storage spaces. Real-time sensor data collection and direct transmission to the backend system allow for proactive quality control measures and early deviation detection.

The integrated system flow is depicted in Figure 7, which shows how raw material intake, quality inspection, batch processing, environmental monitoring, centralized data storage, and dispatch interact. The flow shows how digital processes and IoT-driven monitoring work in tandem to preserve end-to-end traceability and coordinated quality control. To assess system behavior under practical operating settings, twelve batches with different quality characteristics were employed in a simulated production.

0.5 Prototype Dashboard Interface

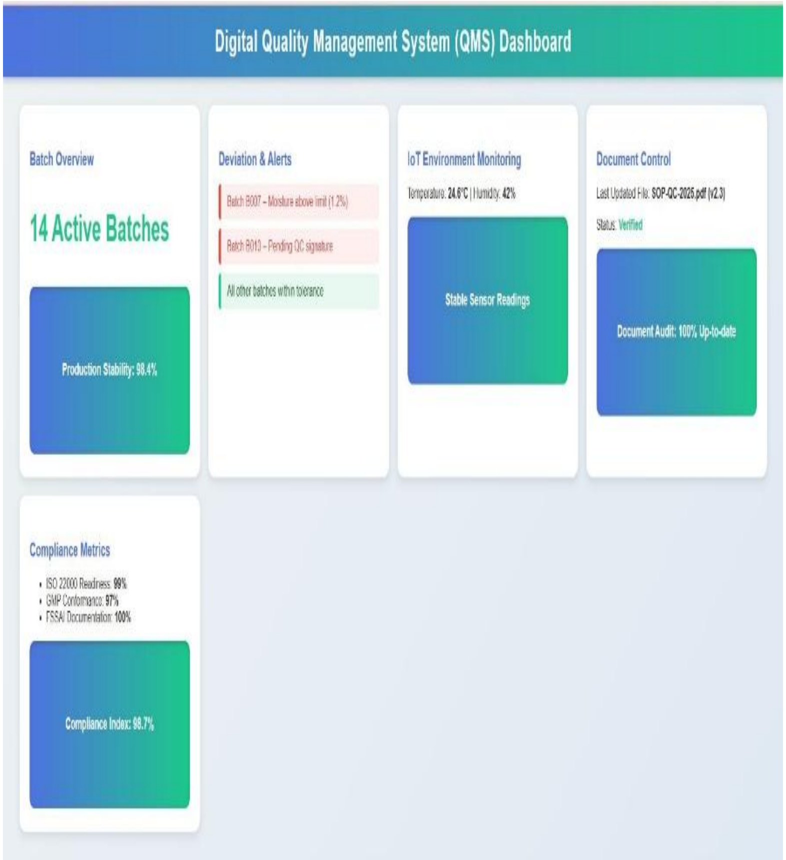
A web-based dashboard was developed to provide real-time visibility into production quality, environmental conditions, and batch status. Implemented using Angular and HTML, the dashboard consolidates IoT sensor readings, batch-level analytics, deviation alerts, and document status into a unified interface. Figure 8 presents the prototype dashboard layout, designed to enable rapid assessment of operational conditions without reliance on multiple standalone tools.

The dashboard displays interactive cards summarizing active batches, environmental stability, detected deviations, and documentation status. Live data streaming from IoT sensors ensures that key performance indicators reflect current production conditions. By centralizing operational and quality data, the dashboard reduces decision latency, improves situational awareness, and supports timely corrective actions by quality personnel.

0.6 Batch Quality Metrics Analysis

Python-based processing modules that assess important factors including purity, moisture content, and pH levels were used to perform batch-level quality analytics. Early detection of departures from permissible limits is made possible by the automated logging, analysis, and visualization of each batch. The batch quality metrics for twelve simulated manufacturing batches are shown in Figure 9.

Fig. 8: Prototype web dashboard interface



Digital Quality Management System (QMS) Dashboard

Batch Overview

14 Active Batches

Production Stability: 98.4%

Deviation & Alerts

Batch B007 – Moisture above limit (1.2%)

Batch B013 – Pending QC signature

All other batches within tolerance

IoT Environment Monitoring

Temperature: **24.6°C** | Humidity: **42%**

Stable Sensor Readings

Document Control

Last Updated File: **SOP-QC-2025.pdf (v2.3)**

Status: Verified

Document Audit: 100% Up-to-date

Compliance Metrics

- ISO 22000 Readiness: **99%**
- GMP Conformance: **97%**
- FSSAI Documentation: **100%**

Compliance Index: 98.7%

Stable and consistent manufacturing conditions were indicated by pH values between 6.8 and 7.4, moisture content between 2

TABLE 1: Sample batch metrics

Batch	Purity (%)	Moisture (%)	pH Level
B001	97.4	3.2	7.1
B002	95.8	2.5	6.9
B003	98.2	4.1	7.0
B004	96.5	3.8	7.2
B005	97.0	3.0	7.1
B006	96.8	4.3	6.8
B007	95.9	3.5	7.0
B008	98.0	2.9	7.3
B009	97.3	3.7	7.2
B010	96.6	4.0	7.1
B011	97.5	3.6	6.9
B012	96.9	3.3	7.0

0.7 IoT Sensor Stability and Environmental Monitoring

Because many nutritional substances are sensitive, environmental stability is crucial in the manufacture of sports nutrition. Temperature and humidity sensors with Internet of Things capabilities were set up to provide data every 10 minutes. Sensor stability throughout a 24-hour monitoring period is depicted in Figure 10, with humidity at 42 ± 1.5% and temperature at 24.6 ± 0.3°C.

These little deviations show how well the environment is controlled and show how well the system can identify small changes that can have an impact on the quality of the final output.

Preventive action is made possible by ongoing monitoring before variations become batch non-conformance.

0.8 Quality Compliance Performance Tracking

Quality compliance across ISO 22000, GMP, and FSSAI standards was assessed before and after system deployment. Figure 11 illustrates improvements in compliance performance following automation. Doc- umentation readiness and conformance levels increased significantly, reflecting the effectiveness of digital workflows, automated verification, and real-time monitoring.

Fig. 9: Batch quality metrics analysis

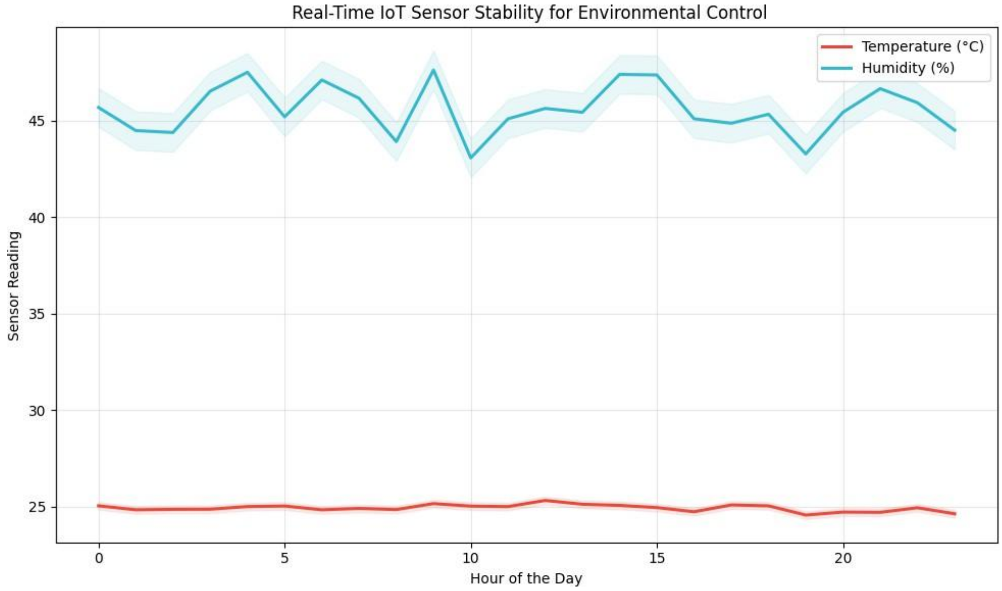


Fig. 10: Real-time IoT sensor stability

0.9 Deviation Tracking and Workflow Optimization

The deviation tracking module records and categorizes anomalies based on affected parameters, severity, and batch association. Figure 12 demonstrates a substantial reduction in monthly deviations following implementation. Manual processes recorded 12–14 deviations per month, whereas the automated system reduced this to 3–5 deviations per month. Automated alerts and structured workflows reduced batch release times from approximately 48 hours to less than 12 hours.

In order to provide thorough reporting and traceability, the system logs every deviation along with batch identifiers, impacted parameters, and severity levels. Stress testing with 25 concurrent users and 10,000 stored records under simulated conditions showed database query execution rates of less than 0.5 seconds and average backend response times of about 180 ms per API call. These outcomes validate the implementation's resilience and scalability for medium-to-large production settings.

End-to-end traceability, ongoing environmental monitoring, automatic compliance verification, and proactive deviation management are all accomplished by the established system. The findings show how Batch quality consistency, environmental stability, regulatory compliance efficiency, deviation reduction, and user productivity were among the performance dimensions used to assess the suggested IoT-enabled quality monitoring framework, which is backed by a digital Quality Management System (QMS). Twelve batches of simulated production datasets, continuous environmental sensor readings, and quality documentation records were used to calculate performance measures. The results of the system were compared to baseline parameters that reflect traditional manual quality control procedures. well IoT-enabled quality monitoring can be integrated with digital quality management infrastructure to improve operational effectiveness and quality assurance in the production of sports nutrition.

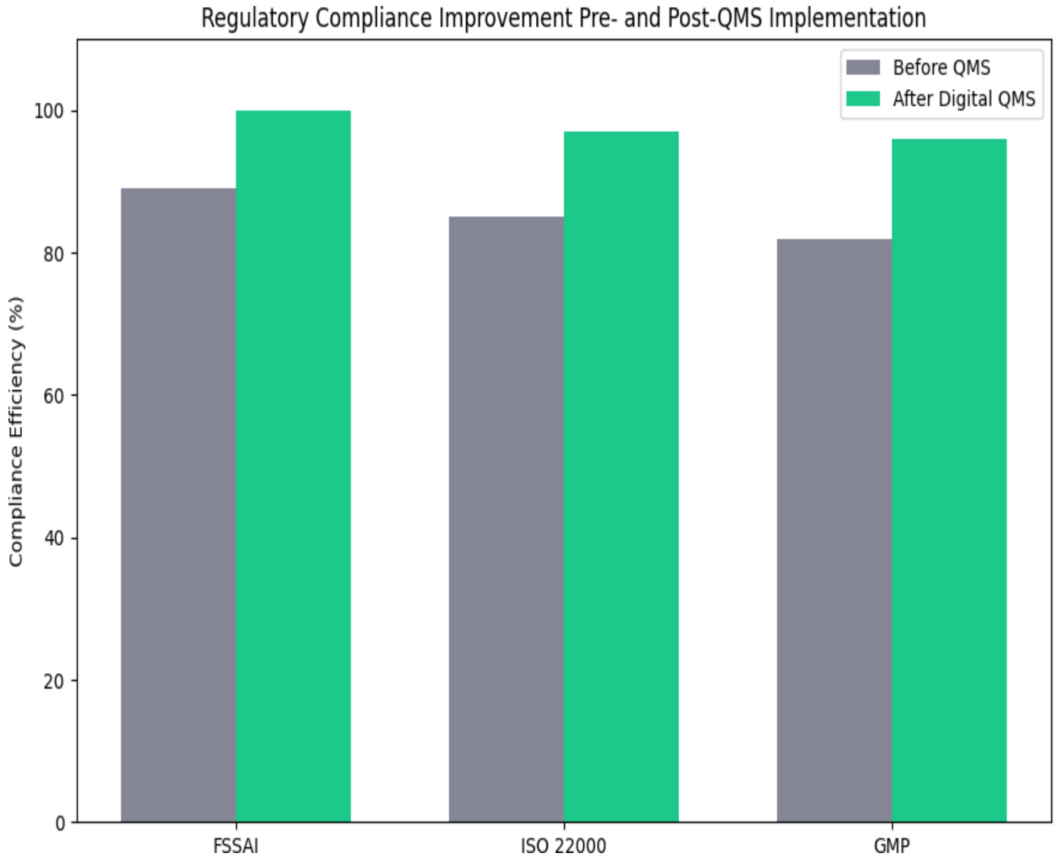


Fig. 11: Quality compliance performance improvement

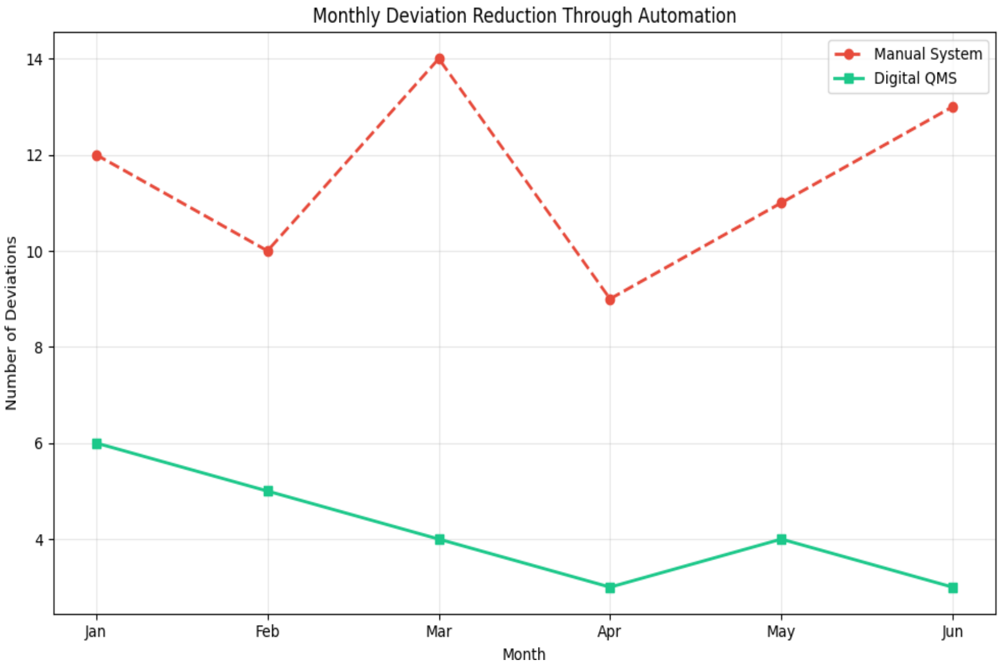


Fig. 12: Monthly deviation reduction through automation

V. Results And Discussion

0.10 Overview of System Performance

Overall, the findings show significant gains in every assessed area, demonstrating the value of incorpo- rating IoT-based monitoring, workflow automation, and centralized data analytics into sports nutrition production operations. Batch parameter consistency during a six-month simulated period is shown in Figure 13, which highlights decreased variability in pH, moisture content, and purity values after system implementation.

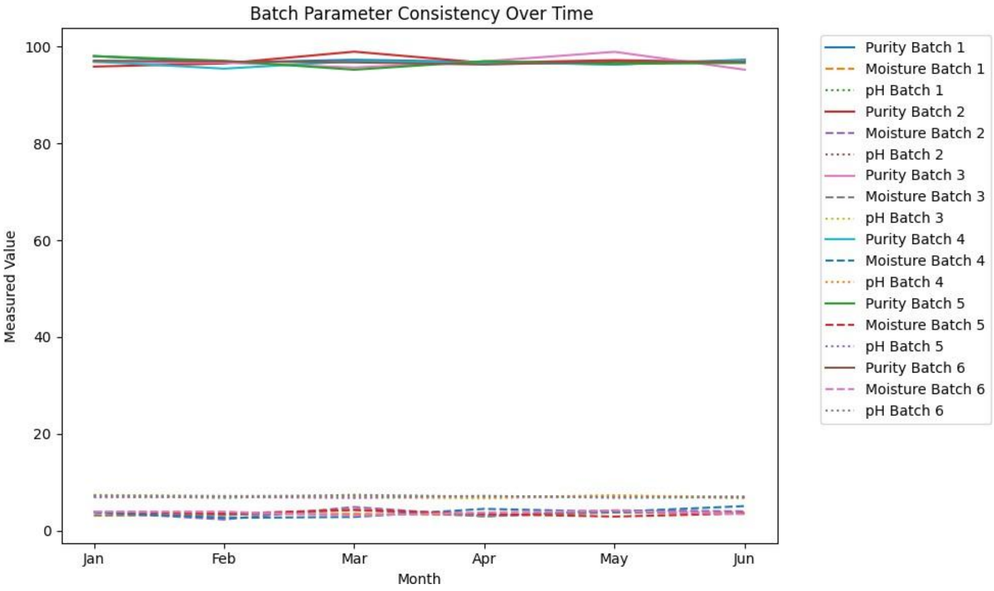


Fig. 13: Batch parameter consistency over time

0.11 Quality Compliance and Audit Efficiency

Simulated audit checklists in accordance with FSSAI, ISO 22000, and GMP standards were used to evaluate quality compliance performance. Document availability, batch validation completeness, and deviation resolution status were taken into consideration when assigning compliance ratings to each production batch. The audit ratings obtained before to and following system deployment are summarized in Table 2.

TABLE 2: Compliance audit scores

Audit ID	FSSAI Score	ISO 22000 Score	GMP Score	Overall Score
A001	88	84	81	84.3
A002	90	85	82	85.7
A003	87	83	80	83.3
A004	92	86	85	87.7
A005	89	84	83	85.3
A006	91	87	84	87.3

Discussion: The audit results indicate a consistent improvement of approximately 5–7% in overall compliance scores compared to manual audit processes. These gains are primarily attributed to auto- mated document control, real-time batch validation, and integrated deviation tracking, which collectively reduced human error and improved audit preparedness.

0.12 Environmental Parameter Analysis

Environmental stability was evaluated using hourly temperature and humidity data collected over multiple simulated production cycles. Figure 14 presents a heatmap illustrating environmental variations across a 30-day period.

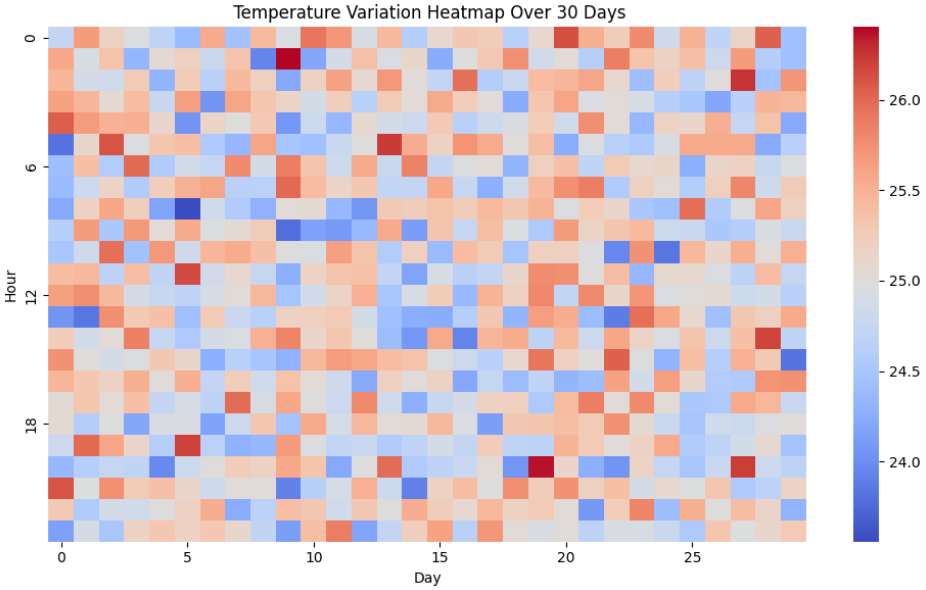


Fig. 14: Temperature and humidity variation heatmap over 30 days

The heatmap verifies that humidity levels were mostly kept between 43 and 47%, while temperature values stayed between 24 and 26°C. These limited working ranges show how well IoT-enabled environ- mental monitoring works to keep manufacturing conditions steady, which is crucial for maintaining the integrity of thermolabile sports nutrition ingredients.

0.13 Process Improvement and Deviation Analysis

Variations in the environment, moisture imbalance, and inconsistent documentation were among the categories in which operational deviations were examined. The monthly distribution of deviations over a six-month period after system deployment is shown in Figure 15.

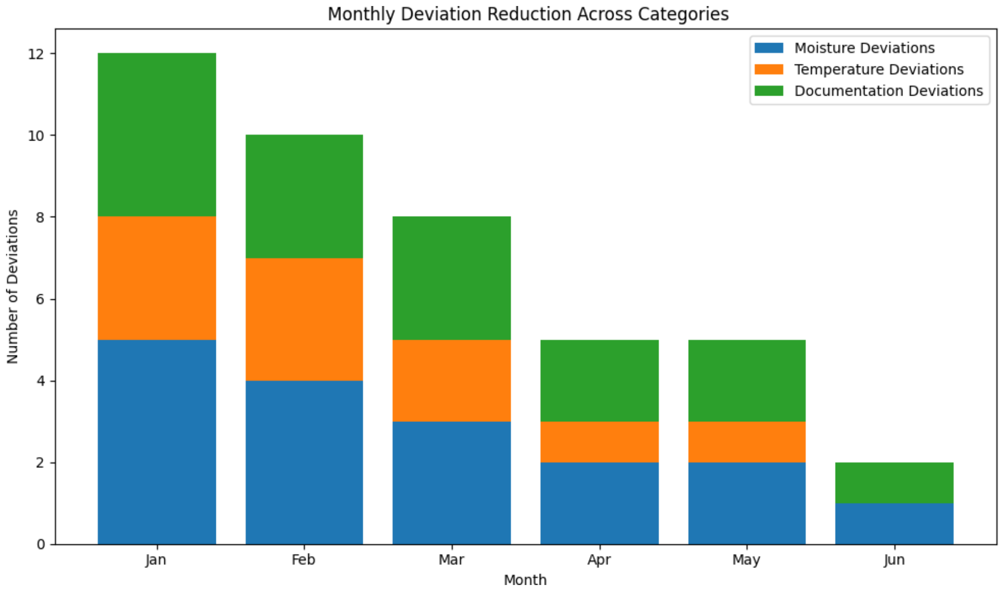


Fig. 15: Monthly deviation reduction across categories

The results show a significant reduction in overall deviations, with environmental-related deviations declining to zero by the sixth month. Documentation-related deviations were minimized due to automated version control and validation workflows. These findings confirm that real-time monitoring combined with automated quality processes substantially enhances operational reliability and reduces non-conformance risks.

0.14 User Efficiency and System Usability

System usability was evaluated by measuring the time required for batch review and deviation resolution before and after implementation. Manual batch review processes required approximately 35–40 minutes per batch, whereas the digital dashboard reduced this duration to 8–10 minutes. Figure 16 illustrates the improvement in user efficiency

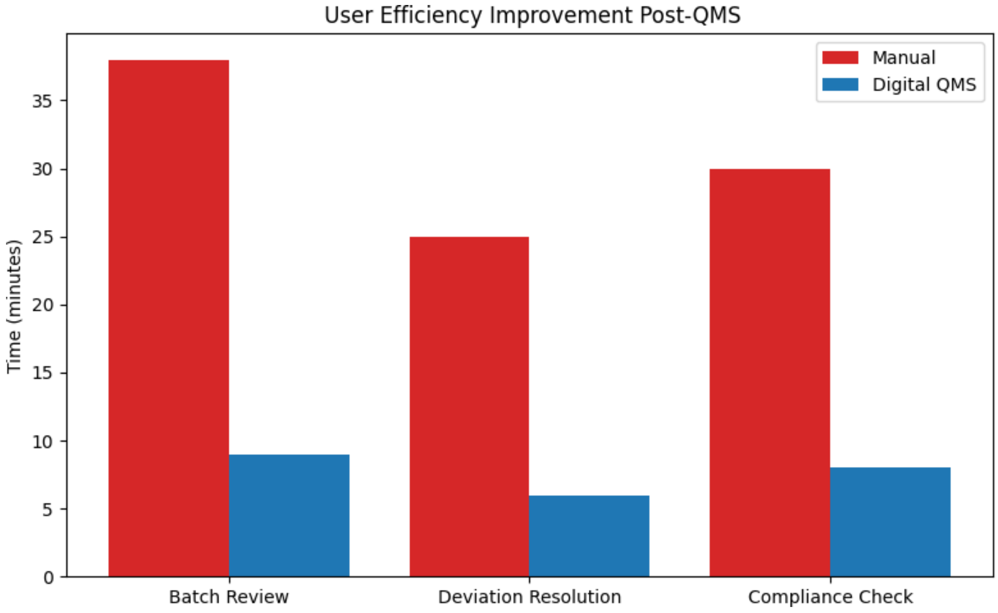


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Fig. 16: User efficiency improvement following digital implementation

The reduction in review time highlights the effectiveness of centralized dashboards and real-time alerts in streamlining quality operations. Improved usability enables quality personnel to focus on higher-level analysis and decision-making rather than manual record verification.

1 Vi. Conclusion And Future Work

The proposed system has certain limitations. First, validation was conducted using simulated datasets, which may not capture all real-world industrial variations. Second, system performance depends on net- work reliability and sensor calibration accuracy. Third, large-scale deployment may introduce scalability and cybersecurity challenges that require further investigation. Future work should include real industrial deployment and long-term stability evaluation.

The design, implementation, and assessment of an IoT-enabled quality monitoring system backed by a digital Quality Management System for sports nutrition production were described in this study. The suggested solution combines centralized data management, automated will investigate sophisticated machine learning models for adaptive process optimization and predictive quality predictions, whereas the current implementation concentrates on environmental and batch-level quality indicators. The results of this study offer a scalable blueprint for Industry 4.0-ready quality assurance systems and practical insights into the use of IoT-enabled quality monitoring in sports nutrition production.

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compliance procedures, batch-level quality analytics, and real-time environmental monitoring into a single digital platform. The findings show that workflow automation and continuous monitoring greatly improve operational responsiveness, regulatory compliance effectiveness, and process stability.

Measurable gains in batch consistency, environmental control, audit readiness, deviation reduction, and user efficiency were proven by experimental assessment utilizing simulated production data. Early quality deviation identification was made possible by the integration of IoT sensors, and traceability and audit readiness were guaranteed by digital documentation and automated validation. When com- bined, these capabilities move quality assurance from inspection-based, reactive methods to data-driven, proactive monitoring.

The suggested framework’s modular design facilitates scalability and upcoming improvements, such as the incorporation of intelligent decision-support and predictive analytics modules. Future research

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