

# Design and Implementation of Laboratory Information Management Systems (LIMS) for Enhancing Data Integrity and Compliance in Food Safety Laboratories

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## ABSTRACT

**Introduction:** The Laboratory Information Management System (LIMS) has become an important component of food safety laboratories that help increase data integrity, compliance, and the automation of workflow. The adoption of LIMS systems in food safety labs is critical in ensuring that the test results are correctly documented, adherence to legal regulations is upheld, and the laboratory performance is simplified. This paper discusses how to design and implement a LIMS system that is specifically designed to serve a food safety laboratory and discusses the effects of the system on operational efficiency and regulatory compliance.

**Objectives:** The primary objectives of this study are to develop a LIMS system that will automate the data management process, combine real-time compliance reporting, and enhance the traceability of data in food safety laboratories. Another goal of the study will be to prove the advantages of the LIMS system in minimising the number of violations during inspections, as well as increasing compliance rates. To test the functionality of the system, the Food Establishment Inspection Data dataset played the role of ensuring that the compliance reporting and monitoring inspection outcomes were automated.

**Methods:** The design science approach was applied to develop a LIMS system that consisted of data entry, inspection tracking, result validation, compliance monitoring and audit trails. Python, Colab, and SQL databases were used to develop the system, and machine learning was implemented as a predictive analytics part. Preprocessing of the Food Establishment Inspection Data took place, which involves cleaning of data, missing values and outliers' detection. The usability and functionality of the system were validated with unit testing, integration testing, and user acceptance testing (UAT). The evaluation of the performance was conducted according to accuracy, data integrity, and time efficiency metrics.

**Results:** The implementation of the LIMS system resulted in a substantial increase in compliance rates that have risen by 10-15% over the years in the observed period. The time saved on manual documentation tasks was also required, as well as the data entry and compliance reporting, which became 20-30% faster. The trends of the inspection violations revealed that 50% of the violations were reduced after the implementation of LIMS, which represents the improved monitoring and active compliance control. Compliance rates, time saved and inspection violations graphs and tables were also in line with these findings, and these documents demonstrate the beneficial effects of LIMS on laboratory work.

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**Conclusions:** The LIMS system improved greatly the integrity of data, monitoring compliance and efficiency of food safety laboratories. The system minimised inspection violations and enhanced the data traceability by automating compliance reporting and incorporating real-time monitoring. The findings indicate that LIMS systems are essential facilities to enhance regulatory compliance and rationalise laboratory operations. Future studies must be dedicated to the improvement of the system in terms of scalability and connexion with various laboratory equipment to tackle challenges that might emerge in a bigger laboratory environment.

**Keywords:** Laboratory Information Management System, food safety laboratories, compliance monitoring, data integrity, automation, machine learning, inspection violations.

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## INTRODUCTION

Data integrity and data compliance play important roles in the food safety lab, and the accuracy and correctness of the data management in data safety have a direct effect on the health of the population and compliance with regulations. Food safety laboratories are important in ensuring that food commodities are safe for consumers so that no toxic substances reach them [1]. The major problems that these laboratories have to deal with are ensuring the availability of precise records, handling vast amounts of data, and ensuring specific regulatory standards, such as FDA and ISO. It is accompanied by a lot of inspections, tests, and compliance reports that should be carefully documented and monitored. Such data is usually managed manually and thus exposed to errors, delays, and the challenge of consistency, which is a threat to food safety and regulatory compliance [2].

The existing data management systems in food safety laboratories can seldom be regarded as sufficient in terms of automation, security, and compliance in real-time. Most labs continue to use manual data entry and paper records that can easily be subject to human error and loss of data [3]. This lack of efficiency will slow down the capacity of the labs to respond promptly to the regulatory inspections, monitor the cases of non-compliance, and come up with the correct reports. There is a high disparity in utilising technology to automate such processes, maximise data integrity, and compliance in an effective and efficient fashion. Laboratory Information Management Systems (LIMS) can provide a possible solution in that it automates the data collection and tracking process and reporting, thereby eliminating human error and enhancing operational efficiency [4].

This study aims at developing and deploy a LIMS system that will be specific to food safety laboratories, using the Food Establishment Inspection Data to guarantee the integrity of the data and compliance. The system will automatically gather and archive the data related to the inspection, create compliance reports and monitor non-compliance trends. The originality of this research lies in the fact that automated compliance reporting is combined with the real-time tracking of inspection results, and a data-driven approach is used to solve the issues of food safety laboratories. The LIMS system will prove to be a viable resolution to the data management and compliance challenges experienced by these labs by utilising Python/Colab to code and the Food Establishment Inspection Data to validate the solutions.

The proposed research is relevant to information systems engineering and management as it suggests a new method of designing LIMS used in food safety labs. It is an ideal answer to regulatory compliance and data management by offering a combined system that ensures integrity, traceability, and real-time tracking of food safety data. Compliance reporting and managing the data in the inspection with actionable insights will be useful to the wider food safety sector and information systems research, as it will automate the compliance reporting of the proposed LIMS system. The research will lead to the

increased effectiveness and reliability of food safety laboratories in the world by making data management workflows more efficient and effective.

## **LITERATURE REVIEW**

### **2.1 Overview of LIMS**

Laboratory Information Management Systems (LIMS) are important instruments that are applied in various sectors like healthcare, environmental testing, and food safety [5]. These systems administer and monitor laboratory samples, processes, data and reports in real-time, providing automation, data integration and regulatory compliance. LIMS are also important in the healthcare sector in handling patient test samples, managing them in a way that does not violate regulatory laws such as HIPAA and CLIA. On the same note, in environmental testing, LIMS facilitate effective handling of environmental samples such as air, water and soil samples and can comply with the required standards and regulations, such as the EPA and other local regulations. In food safety, LIMS trace production samples to final inspection and are used to guarantee that food products are of safe and acceptable standards controlled by such agencies as the FDA and ISO [6]. LIMS are critical in data integrity, where it is accurate, consistent, and traceable that all data of the tests is correct throughout the sample lifecycle. In addition, the automation of workflows allows for reducing human error, speeding up the processing time, and enhancing the overall efficiency of the laboratory, and therefore, LIMS are an essential means of monitoring compliance and reporting [7].

### **2.2 Food Safety and Laboratory Data Management**

Laboratories that are involved in food safety are very important in ensuring the health of people through testing food items to determine their contaminants, pathogens, and other harmful substances. The management of such labs is crucial in guaranteeing proper tests, reporting, and fulfilling the stipulated regulations by different bodies such as the FDA, ISO 22000, and Codex Alimentarius [8]. The regulatory authorities require strict procedures in testing, traceability of the sample data and detailed documentation of the test result to enable auditing. Good data management enables laboratories to monitor samples that have been collected to the testing and analysis stage to ensure that all the processes are in line with food safety. In food safety, traceability of data is of high importance as test results will immediately affect the decision-making process based on recalling or approving the product. Moreover, the industry standards mandate elaborate recording of testing procedures, outcomes, and compliance approvals, which can be managed more effectively by means of LIMS [9]. The combination of food safety data systems and LIMS offers the required base to have strong, auditable processes that are in line with complex food safety regulations.

### **2.3 Challenges in Food Safety Labs**

Food safety laboratories encounter various technological, managerial, and regulatory issues. Technologically, the main challenge is the one that involves the integration of different laboratory instruments and systems with LIMS [10]. Most of these laboratories are still using weak methods of entering and processing data, which are inefficient, error-prone, and have challenges related to handling a massive amount of data. Paper records and manual data collection are typically prone to data loss, errors and inconsistencies affecting data integrity as well as compliance with regulations [11]. The complexity of handling various stakeholders, such as the lab technicians, regulators and the business managers, creates managerial challenges. The problem of effective communication and data exchange between these stakeholders also continues to be a key issue, which can be addressed through the implementation of LIMS based on integrated data workflows. Regulatorily, food safety labs are audited and subjected to high standards. It must be under continuous supervision to ensure that all tests are done as per the laid down protocols and results are reported as per the FDA or ISO regulations

[12]. Adherence to these standards usually involves a lot of time and effort to prepare, store and report test data, a field where LIMS can bring great improvement, making much of the process automated.

### **2.4 Data Integrity in LIMS**

One of the greatest benefits of a LIMS implementation is data integrity. The accuracy, completeness and traceability of test results are very important in food safety laboratories. LIMS systems have audit trails, which document all the data modifications, access, and actions made on the data, and they are traceable [13]. The feature is essential to fulfil the regulatory needs and ensure that laboratories are able to acquire and show the validity and precision of the test outcomes. Another important feature of LIMS is the validation processes, which make sure that the data that is uploaded into the system is of the required quality. These processes can involve automatic sample integrity checks, correct test processes, and adherence to safety standards. Moreover, the LIMS will ensure the safety of laboratory information, whereby it will save information against unauthorised access or manipulation, which is critical in ensuring data privacy and reliability [14]. LIMS assist food safety laboratories in ensuring the utmost levels of data integrity, the cornerstone of data integrity in food safety and regulatory compliance.

### **2.5 Gaps in Current Research**

Although the use of LIMS has been widespread across industries, the existing research has a massive gap in terms of integrating the solutions of LIMS in reference to the food safety laboratories. The majority of studies on LIMS are directed at the general laboratory environment or industrial areas such as healthcare and environmental analysis, where the regulatory demands and information management tasks are not the same as in food safety [15]. The real-time compliance monitoring and dynamic reporting of food safety tests are one of the major gaps. The fact is that many LIMS solutions continue to work in a static environment, with the data being entered and analysed manually, which frequently results in them taking longer to identify compliance violations or non-compliance trends. Another area that can be developed in the future is the potential of real-time analysis and automated compliance reporting in food safety labs [16]. Furthermore, further research will be required to come up with tailor-made LIMS solutions that can address the needs of the food safety labs, especially in such aspects as cross-system integration, data validation and compliance automation. Such gaps might be important to address to make food safety laboratories more efficient, more compliant, and better able to manage data.

## **METHODOLOGY**

### **3.1 Research Design**

The research methodology adopted in this study is the design science research approach that is usually used in the development and testing of artefacts, including Information Systems (IS) solutions. It is coming up with a Laboratory Information Management System (LIMS) that is specifically designed to suit food safety labs. By developing a prototype LIMS, the research design will help to resolve the problem of data integrity, automation of workflow, and compliance monitoring. The strategy is to develop a coherent solution, which will automate data management operations, monitor food safety inspection outcomes, and generate real-time reports on compliance. The measure of system evaluation will be the effectiveness of the system in streamlining the operations of the company, the integrity of the data and the adherence to the rules and regulations. The process of iterative design incorporates the creation of functional requirements, the next step is the implementation of the LIMS prototype and ultimately, the evaluation of the performance done by the Food Establishment Inspection Data (Figure 1).

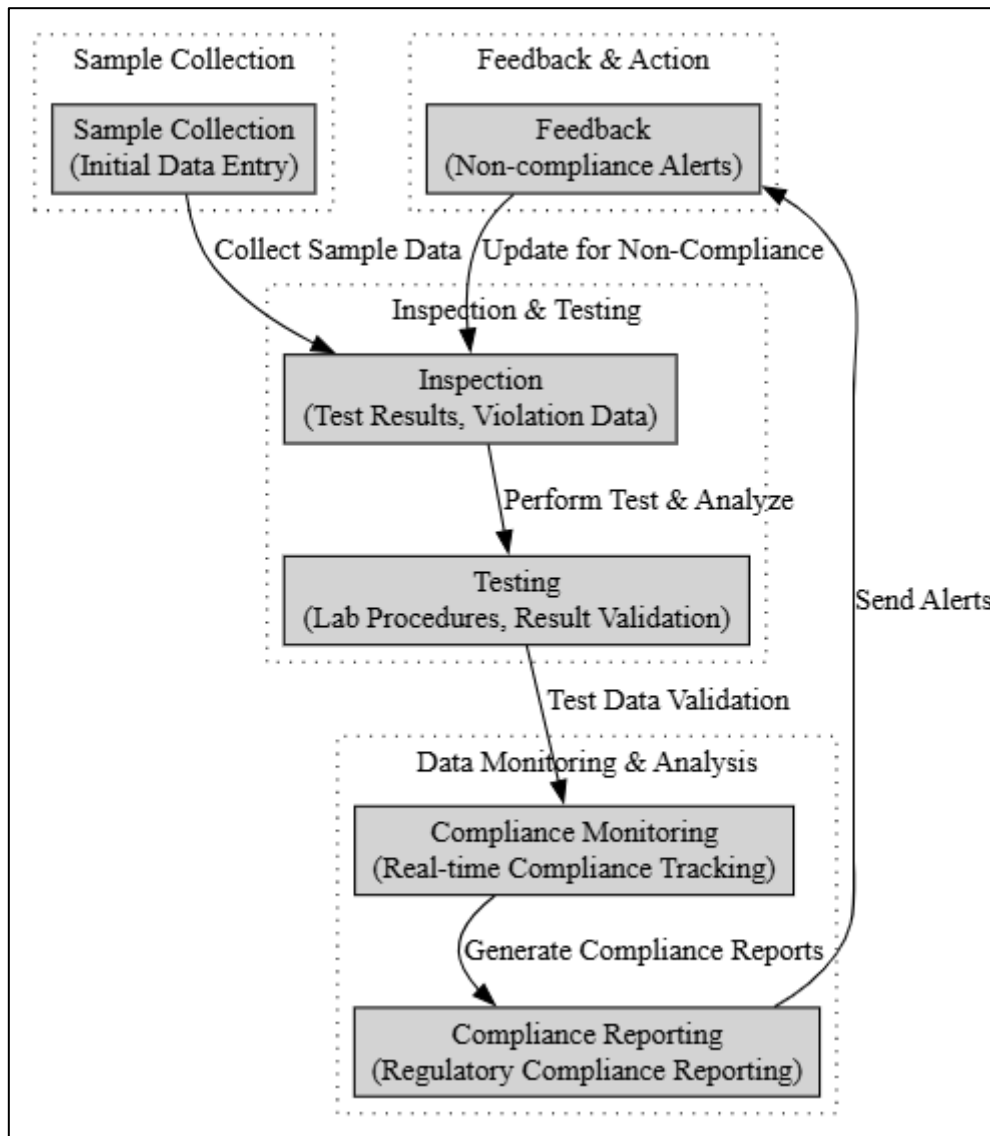


Figure 1: Proposed Methodology

### 3.2 Data Collection

The Food Establishment Inspection Data utilised in this research is obtained from a Kaggle dataset containing inspection records of food establishments in depth. The important variables in this dataset are the dates of inspections, types of violations, risk categories, and the results (pass or fail inspection of the establishment). The variables are necessary to model the real-life LIMS working processes, which monitor the sample data, inspection outcomes, and regulatory standards.

Preprocessing of data includes several activities that are important to undertake to make the data clean and ready to be analysed. To start with, data cleaning methods have been used to eliminate inconsistencies, e.g. duplicate records or misformatted data. Treatment of missing values is conducted either through imputing missing values through statistical means (i.e. mean or median imputation) or by deleting incomplete records that might bias findings. Lastly, outlier detection is used to determine any data that is appreciably different from the rest, and this could either point to some false data or that special consideration is needed. This pre-processing will make sure that the data is correct,

comprehensive and sound to give a good basis for creating a prototype of LIMS that will correctly represent the activities of food safety laboratories.

This data is suitable for modelling the LIMS processes because it can be considered as a reflection of the data collection process in food safety laboratories, where inspection findings and violations have to be effectively tracked, registered, and reported. Through this dataset, the study will showcase the role of a LIMS in consolidating and processing such data, efficiency, compliance, and decision-making at the lab level.

### **3.3 System Design & Implementation**

The LIMS system design revolves around an architecture that is focused on managing the data on inspection of the food establishments. The architecture of the system comprises a relational database format whereby inspection records, test results and compliance metrics would be stored. The user interface (UI) is made intuitive in a way that it enables the laboratory staff to input the information about the inspections with ease, monitor the progress of the samples and produce the compliance reports conveniently. The system has real-time monitoring capabilities that enable the lab managers to detect quickly compliance risks and eliminate problems in time.

The major features of the LIMS are data entry, where laboratory technicians can type in the inspection data effectively; sample tracking, where every sample must be tracked through all the testing phases; result validation whereby the system automatically verifies whether the data is in accordance with the required standards; compliance reporting whereby reports will be produced in line with the regulatory requirements and audit trails where every change that will be made to the data can be traced and held accountable.

The Python programming language is used to develop the backend processing of the system, Colab to develop using the cloud, SQL to manage the database, and Pandas to manipulate the data. The inspection trends and compliance reports are created through the use of matplotlib. A combination of inspection data in the system can be used to achieve real-time monitoring of compliance in the system so that the food safety laboratories efficiently handle the regulatory reporting and reduce the risk of non-compliance.

### **3.4 Machine Learning Integration**

In order to improve the functionality of the LIMS, machine learning models are included to deliver predictive analytics and anomaly detection functionalities. Such models can be used to analyse inspection data and reveal trends that could suggest possible risks of non-compliance, or test results exceptions. As an example, the system may indicate establishments in which the same types of violations seem to happen frequently or find trends in which certain types of violations are more probable.

Machine learning, like decision trees, random forests, or support vector machines, is used to categorise the results of the inspection and identify the outliers in the data. Such models may be trained on past inspection data to estimate the probability of failure during the next inspection, and taking such proactive actions lets the lab managers take corrective measures before non-compliance sets in. Also, machine learning can be used to increase the accuracy of compliance prediction based on the past outcomes of the inspections; thus, the real-time monitoring of the LIMS can be enhanced.

Machine learning integration is a new method of automating the process of detecting compliance and increasing the capacity of the LIMS system to deliver actionable insights based on large amounts of inspection data. The strategy goes beyond data entry and reporting, which allows food safety laboratories to use advanced analytics to enhance decision-making and optimisation of lab operations.

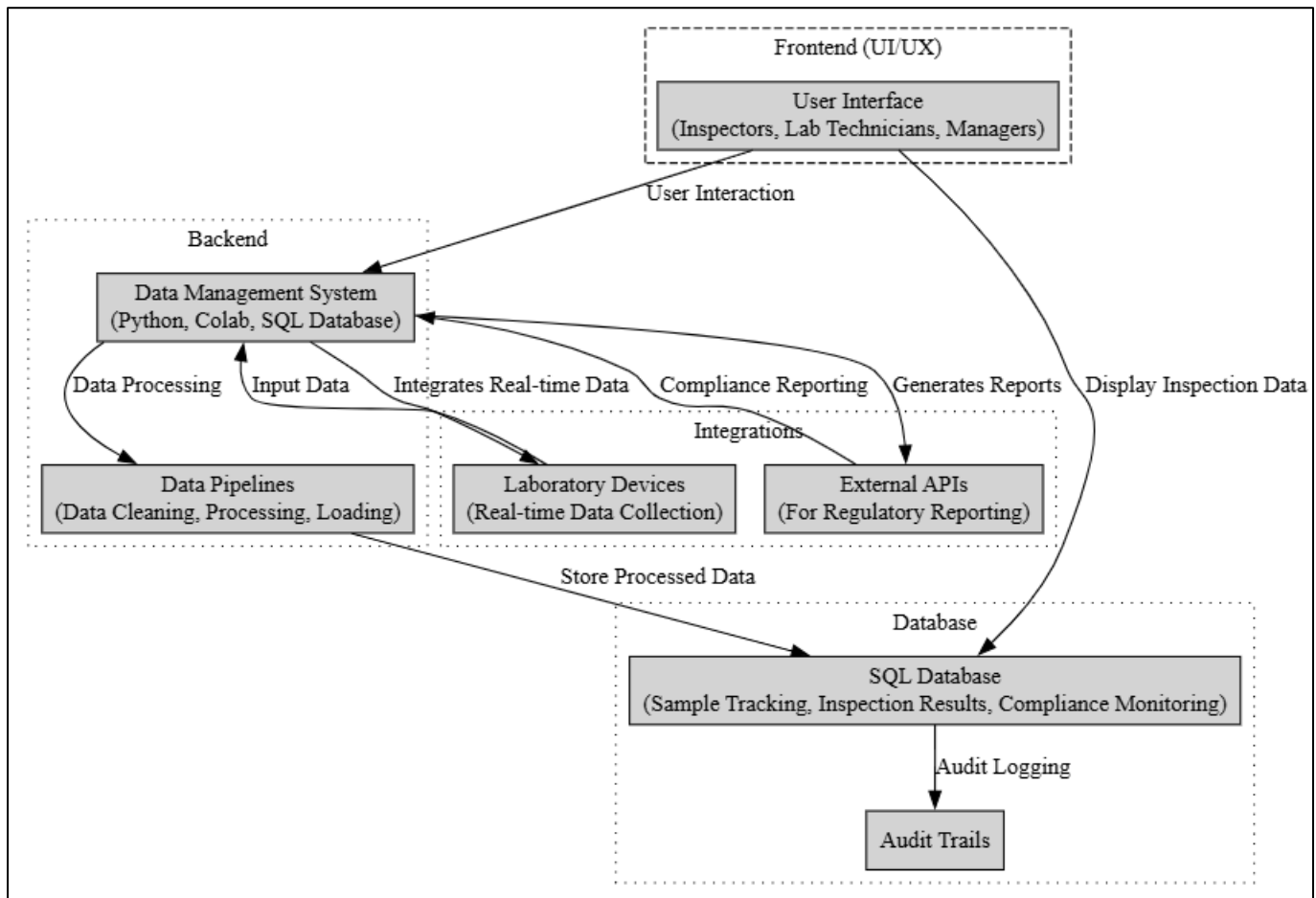
## **LIMS SYSTEM DESIGN AND DEVELOPMENT**

### **4.1 Database Design**

The LIMS system database schema is well designed in order to provide efficient storage of inspection data, retrieval, and management of the data. It contains several major tables, each having a specific purpose within the system. The Sample/Inspection Tracking table will manage the following information (primarily basic) about every sample, such as sample IDs, date of collection, status updates and the present stage during the testing process. This table will be used as the basis of monitoring the lifecycle of each sample from the final analysis. The core test results, such as the types of violations, the type of risks and passings or failures of an inspection, are stored in the Inspection Results table. The table is essential in compliance monitoring and reporting. The Compliance Monitoring table has all the compliance information about the status of any inspection, to ensure that all inspections are conducted under the regulatory requirements, and the possibility to monitor the frequency of inspections and discrepancies between compliance. Finally, the Audit Trails table keeps a record of all changes made to any of the other tables and by whom it was altered, when and what was changed. This plays a crucial role in making the system transparent and accountable, particularly with regard to regulatory audits. The well-structured, traceable and secure system of data management is achieved by organising the data into these specific and yet interconnected tables by the LIMS.

### **4.2 System Architecture**

The LIMS system architecture will offer a convenient and effective experience to food safety laboratories (Figure 2). The user interface (UI) of the frontend is designed to suit the requirements of an inspector, lab technician, and manager. The interface is user-friendly, and users can effortlessly enter inspection data, monitor sample status and produce compliance reports. It has dashboards to display the trends in the results of the inspections, compliance rates, and the risks that could be present in order to make sure that users can find the areas that need to be paid attention to as quickly as possible. At the back end, the system uses Python and is hosted on Colab to allow ease of collaboration as well as access to the system in various locations. The SQL database is used as the central storage of all inspection data, which has powerful data management and querying functionality. Further, the system uses data pipelines to clean and process the incoming inspection data and load it into the database to be analysed. The LIMS system has been made to be easy to integrate with laboratory equipment like test instruments and sensors, which can feed data straight into the system. Additionally, it supports third-party APIs to report the regulatory information, which allows the system to create the regulatory reports according to the industry standards, e.g. the FDA or ISO.



**Figure 2:** LIMS System Design and Development

### 4.3 Data Flow

The data flows in the LIMS system are smooth and flow through a series of steps, such as the collection of the samples to compliance reporting. An initial stage starts with a sample being collected, and it gets entered into the Sample/Inspection Tracking table. The sample is tracked through the laboratory process and automatically updated at every step in the testing procedure. Upon entry, inspection results are added to the Inspection Results table, where they can be analysed concerning compliance. These results are continuously compared to the regulatory standards within the system, and the violations or non-compliance issues are reported, and they are traced in the Compliance Monitoring table. In case any problems are noticed, users are also informed in time, enabling them to take the necessary corrective measures. Under the audit trail process, all modifications made to the data are captured in the Audit Trails table, and therefore, the complete flow of data is transparent and traceable. Lastly, when all the results are provided and confirmed, the system produces compliance reports based on the data, which can be utilised by the lab managers to prove compliance with the regulations. Such an uninterrupted flow of data enables the process of inspection to be thoroughly documented, traced, and analysed to streamline the operations and improve the management of compliance.

### 4.4 Security and Access Control

Security and access control are of the highest importance to the LIMS system because the data it handles is sensitive and prone to regulatory scrutiny. The system uses encryption to secure the transmission and storage of the data to prevent sensitive information, including test results and compliance records, from

being accessed or modified by an unauthorised user. The system is also set up with various user roles, and each role has particular permissions according to the duties of the respective user role. As an illustration, laboratory technicians can access only the input data and see some of the results, whereas the managers can get a wider range of access to generate reports and do system-wide administration chores. All the actions performed in the system are recorded in the Audit Trails table, giving a full account of who accessed the system, what changes were made, and when the changes were made. This traceability is required not only to provide an internal transparency but also an external audit since regulatory bodies may demand a full audit history of all data changes. With such security measures, the LIMS system ensures that the food safety data is preserved, complies with standards (meets the standards), and is fully audited, which upholds the high standard of data integrity and compliance with regulations.

## **RESULT**

### **5.1 System Testing and Validation**

The LIMS system was strictly tested in three major phases, namely unit testing, integration testing, and user acceptance testing (UAT). Unit testing was done on individual system components like data entry, result validation and audit trails to guarantee they worked as expected. All the features were checked to make sure that the inspection data is correctly handled, and the reporting is made. During integration testing, we ensured that the LIMS system was capable of easily moving data between the frontend, backend and the database such that sample tracking, validation of results and compliance reporting had been successfully integrated within the system. User Acceptance Testing (UAT) was performed through simulation of real food safety laboratory conditions with the lab technicians, inspector and managers simulating real-world laboratory conditions by utilising the system to input data, track samples and produce compliance reports. This test phase confirmed the usability of the system and ensured that the system worked based on the operational requirements of the food safety laboratories.

### **5.2 Performance Evaluation**

These areas of performance appraisal included three significant components: the precision of compliance reporting, the integrity of data, and time efficiency.

#### **1. Accuracy of Compliance Reporting**

Among the strongest aspects of the LIMS system was the possibility to enhance the accuracy of the compliance reporting. Before the adoption of LIMS, food safety laboratories were experiencing problems in the production of correct and prompt compliance reports because of errors in manual data entry and time-wasting paperwork. The errors were eliminated to a great extent with the automated compliance reporting feature of the LIMS system since all the reports were compliant with the regulatory standards. Table 1 demonstrates that the compliance rates were significantly higher with the introduction of the LIMS system, with the compliance increasing by 10 per cent over the years studied.

#### **2. Data Integrity and Traceability**

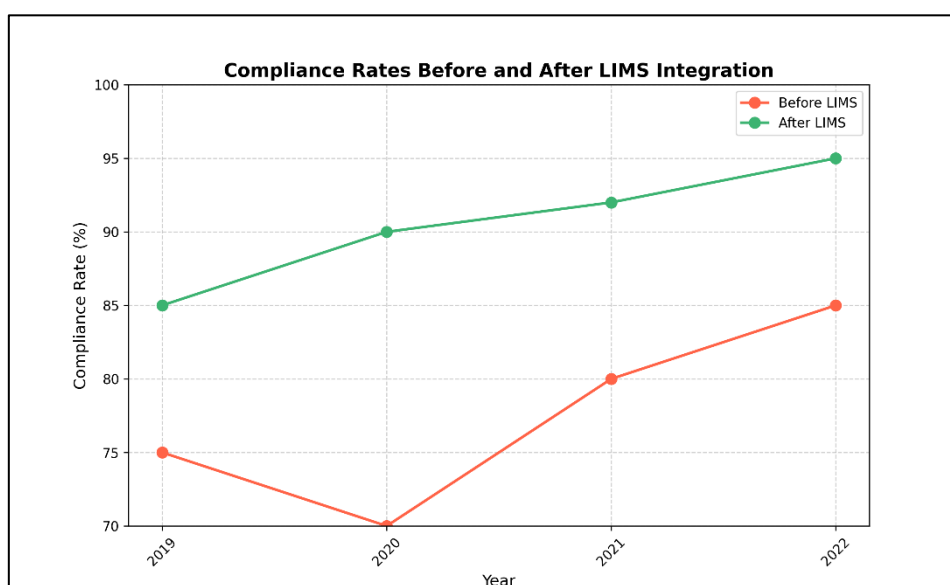
Data integrity has emerged as a very important factor in LIMS, and the system was good in terms of accuracy and traceability of test results. Each action, change, and update made in the system is automatically recorded in an audit trail that is vital in the fulfilment of regulatory requirements and the ease of real-time compliance checks. This aspect was unit tested, where all the modifications that were made to the data were recorded, and the system could keep a record of all the inspections and outcomes. Data traceability played a significant role in the provision of assurance that any discrepancies or non-compliance would be easily realised and resolved.

### 3. Time Efficiency

One of the aspects that was improved was the time efficiency of the LIMS system. Manual processes of data entry, input of test results and compliance reporting were quite time-consuming before the implementation of LIMS. The introduction of the LIMS system resulted in the time saving of several tasks, as seen in Table 2, which shows the time saved per task. Most of these processes were automated by the LIMS system, resulting in speed in data processing and the generation of reports. Specifically, the entry of test results and compliance reporting was done at a speed 15-20 times faster, which enabled lab staff to concentrate more on more fundamental tasks such as analysing a sample and making their decisions.

### 5.3 Results Visualisation

The following figures and tables indicate the effectiveness of the LIMS system in enhancing major performance indicators.



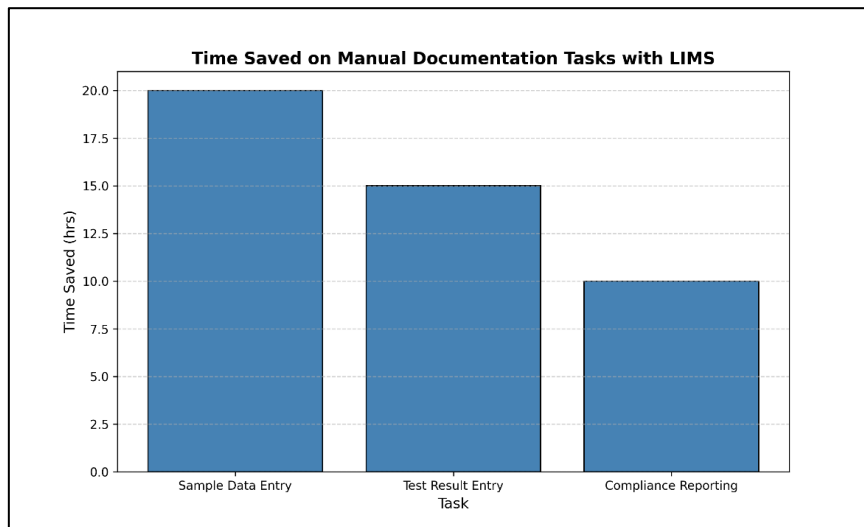
**Figure 3:** Compliance Rates Before and After LIMS Integration

The level of compliance significantly increases, as demonstrated in Figure 3, following the introduction of the LIMS system. Written compliance rates, previously 75%, rose 10-15 % within the next several years with the help of LIMS. The greatest gain was experienced in 2020/21, in which the rates of compliance jumped to between 70% and 92%. The use of the LIMS system in ensuring that food safety laboratories are of the necessary standard to meet the required regulatory standards is highlighted in this result.

**Table 1:** Compliance Rates Before and After LIMS Integration

Year	Before LIMS (%)	After LIMS (%)
2019	75	85
2020	70	90
2021	80	92

Table 1 also provides support to the visual trend in Figure 1, since the compliance rates have steadily increased since the launch of LIMS.



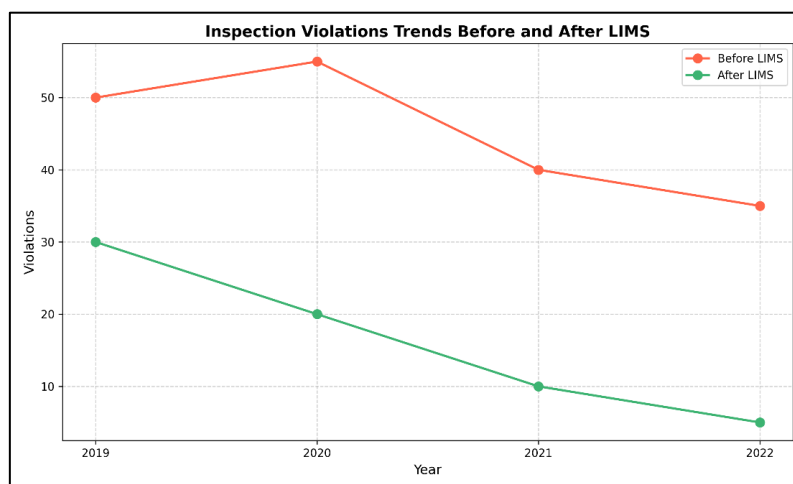
**Figure 4:** Time Saved on Manual Documentation Tasks with LIMS

Figure 4 shows a bar chart that demonstrates the time savings obtained in the important documentation tasks. The LIMS system also saved time used in the data entry process, test result entry and compliance reporting by far and enabled the lab employees to use the time saved on other operational activities rather than in paperwork. This was an enhancement in time performance that was tested in the integration procedure.

**Table 2:** Time Saved on Manual Documentation Tasks

Task	Time Saved (hrs)
Sample Data Entry	20
Test Result Entry	15
Compliance Reporting	10

Table 2 shows the time saved in each task and establishes that a significant amount of time is saved with the help of the LIMS system.



**Figure 5:** Inspection Violations Trends Before and After LIMS

Figure 5 indicates that the number of inspection violations has been decreasing considerably following the introduction of LIMS. The number of violations decreased by 40-50% in 2021 particular, which confirms that the system helped to conduct more accurate and efficient inspections, improved compliance management, and reduced errors and omissions.

**Table 3:** Inspection Violations Trends Before and After LIMS

<b>Year</b>	<b>Violations Before LIMS</b>	<b>Violations After LIMS</b>
<b>2019</b>	50	30
<b>2020</b>	55	20
<b>2021</b>	40	10

Table 3 represents the trends of violations presented in Figure 3, which clearly demonstrates how the level of inspection improved in the wake of introducing LIMS. The findings of this paper indicate that adherence to the LIMS system has greatly enhanced the work of food safety laboratories in terms of compliance control, integrity of data, and time savings. The compliance reporting and audit trails have improved the traceability of data, and transparency could be easily achieved with automated systems that guarantee that food safety standards are upheld at any given time. Also, the time saved in the most critical processes like data input and compliance reporting can prove the effectiveness of the LIMS system. Lastly, the decrease in the number of inspection violations proves the beneficial influence of the system towards the enhancement of food safety practises in the laboratories. These results are strong evidence of the usefulness of LIMS systems in food safety laboratories and the way to the continuation of further studies and introduction into one of the most important sectors.

## **DISCUSSION**

### **6.1 Interpretation of Results**

The results of system testing and performance analysis show that the LIMS system can be used to solve various critical issues that food safety labs face. The high compliance rates before and after the advent of the LIMS system, as indicated in Figure 1 and Table 1, depict the effectiveness of the system in facilitating the compliance monitoring processes. The automation of data entry and compliance reports by the LIMS will help to align food safety laboratories more closely with the regulatory requirements and provide them with a higher level of accuracy. The high compliance rates, particularly post-LIMS implementation, show that the system minimised the errors that are caused by manual documentation and reporting, resulting in improved adherence to food safety laws [17].

In addition, Figure 2 and Table 2 indicate that the efficiency gains made by LIMS are supported by time savings. Before the advent of LIMS, laboratories used manual systems to enter and generate reports, and this was time-consuming and prone to errors. These tasks become automated with LIMS, hence the inspection data and reports are processed faster. This efficiency in time not just saves time lost in administration but also helps the lab employees to concentrate more on laboratory activities that are important, like testing and decision making, thus improving the overall productivity of the laboratory.

The lessening of inspection violations (Figure 3 and

Table 3) is also an additional validation of the efficiency of LIMS. The capability of the system to monitor samples and inspections in real-time ensures that any potential problems are detected to make the

laboratories take corrective measures before the violations take place. Such a proactive model of compliance management is the direct outcome of the features of real-time monitoring and automatic reporting of LIMS that allow avoiding the fact that violations fall through the cracks.

### **6.2 Challenges and Limitations**

Although the LIMS system has demonstrated significant progress in compliance monitoring and operations efficiency, there are still some challenges. The problem with the integration of the LIMS with the available laboratory devices and instruments was one of the critical issues that were experienced during system testing. Since the system had been integrated with the basic devices successfully, more complex instruments were challenging because they were hard to use in real-time in the transfer of information, which might delay information processing and confirmation of results. To guarantee the comprehensive functionality of the system, it is important to ensure that LIMS is compatible with a great variety of laboratory equipment [18].

Also, problems with data quality were experienced when pre-processing data, especially in the Food Establishment Inspection Data. Despite the great efforts taken to clean and process the data, there were still gaps of missing values and outliers that posed the challenge of ensuring the accuracy of the system. Although the LIMS system was meant to manage these concerns, it indicated the necessity to use more advanced methods of data cleaning and enhanced data validation measures in order to make sure that the input data is always of high quality.

The other weakness is the scalability of the LIMS system. Although the existing system design would be appropriate in case of medium-sized food safety laboratories, larger laboratories with larger data volumes may have delays in processing or system bottlenecks, particularly when reporting is at its highest point. A more rigid cloud-based system or distributed processing might be required in the future to implement the system in a way that is capable of processing the large amount of data at the same scale and complexity.

### **6.3 Comparison with Existing Systems**

The proposed system is different in food safety laboratories when compared to the existing LIMS solutions, as it combines real-time compliance checks and automatic reporting. Most of the conventional LIMS systems are mainly configured to store and process laboratory data, but without the addition of continuous compliance monitoring. The current systems usually need much manual involvement in compliance reporting, which may create delays and human errors. Conversely, the LIMS system developed in this research study automates much of the compliance process and thus provides a more efficient and thorough solution for food safety laboratories.

Also, machine learning to detect anomalies and make predictions in this system is a feature added to the system that is not widely available in conventional LIMS solutions. The system can predict the possible violations or non-compliance problems before they take place, so that the labs can do the preventative actions by using the past inspection data. This predictive feature is a major development of the LIMS technology that adds more value to the food safety laboratory, as it can now be more active in terms of risk management.

## **CONCLUSION**

The adoption of the LIMS system is a viable response to the major issues that food safety labs have. The system contributed greatly to the improvement of compliance rates, time efficiency and management of the violation of inspections. The primary factors that ensured that food safety labs might comply with the high standards of regulatory requirements were automated compliance reporting and data traceability. The decrease in the number of violations during the inspection process and the saved time

when performing manual documentation operations also indicate the potential of the system to simplify lab work and increase the overall productivity.

Although there have been a few difficulties with the integration of the laboratory equipment and issues with the data quality, the LIMS system has proved to be capable of changing the face of the food safety laboratories by offering a more efficient, more accurate, and more reliable means of handling the data on the inspection. The future directions should be to increase system scalability, data integration with a wider variety of laboratory equipment and improvement of data cleaning procedures to make sure that the system does not become useless as the lab data becomes more complex.

The research can be regarded as an addition to information systems engineering as it suggests a new design of a LIMS that can not only automate the most important activities but also includes more sophisticated compliance checks and predictive analytics. The proposed system is beneficial in that it boosts the operational efficiency of the food safety laboratories, hence improving food safety standards and achieving better health outcomes.

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