AUTOMATION OF PAVEMENT MATERIAL TESTING LABORATORY PROCESS

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ABSTRACT

Laboratory automation has revolutionised sectors such as healthcare, education, research, and other industrial laboratories. Pavement Material Testing Laboratories (PMTLs) in the transportation engineering sector particularly in developing countries such as Papua New Guinea (PNG) remain disadvantaged in manual processes. The objective of this study is to assess current practices and past studies and to identify suitable automation technology that is customizable to design and develop an end-to-end automated system for PMTL tailored to the PNG context. The system designed is a simple, customized, web-based application developed to streamline and digitize the workflow of laboratory testing processes. The system developed consists of two main user interfaces: the client and admin panel. The workflow includes request submission, request review, sample registration, data processing, and reporting. Each stage ensures that data flows consistently without duplication or loss. The system is integrated in two parts: the front end and the back end. It integrates Barcoding and Quick Response (QR) coding, a database (MongoDB) as the primary database, and the following tools: PDF QR code generation; library and development tools; version and environment management; and testing and deployment tools. The QR and Bar coding system are used to link the different stages. Database (MongoDB) integrates and automates laboratory processes uninterruptedly, from test request to reporting, aligning with ISO/IEC 17025 requirements. Data gathered through case study survey questionnaires from six major public accredited PMTLs and the seven major road contractors in PNG indicated strong support for automation. The system designed is cost-effective, scalable, and customized for resource-constrained countries, where high-end commercial Laboratory Information Management System (LIMS) solutions may be financially and technically impractical.

Key Words: Laboratory Automation, LIMS, PMT, Laboratory Quality Assurance, ISO/IEC 17025

INTRODUCTION

Globally, laboratory automation has transformed laboratory operational efficiency, data integrity, and decision-making across several sectors, including healthcare, education, research, and other industries. Automated laboratory systems, often implemented through advanced technologies such as LIMS, have enabled end-to-end process integration, real-time monitoring, improved turnaround times, and enhanced compliance, aligning with accreditation standards such as ISO/IEC 17025 [7, 9]. Despite these advances, PMTLs in the transportation sector particularly in resource-constrained countries, continue to rely heavily on manual, paper-based, and fragmented processes. The performance, sustainability, and quality of road pavement structures are fundamentally dependent on the properties of pavement materials that are required to meet specified road design and construction standards. In transportation engineering, the selection and verification of suitable pavement material types rely heavily on accurate, timely, and traceable laboratory testing processes undertaken by PMTL. In resource-constrained countries, meeting the growing demand for road materials requires local sources. These materials are extracted and carefully tested to check whether they are suitable for road material use. Their properties greatly affect how well they perform on the road [13]. With a well-equipped automated PMTL, testing can be done faster and more efficiently, handling many samples at the same time while still meeting project deadlines [1, 4]. The PMT laboratory plays a crucial role in ensuring that pavement materials such as soils, aggregates, asphalt, and concrete are tested rigorously to comply with all road design specifications and standards locally and internationally. In resource-constrained countries such as PNG, PMTL operational workflows are fragmented, and they involve manual effort for test request submission, sample registry and tracking, scheduling personnel and equipment, test data processing, reporting, and billing. These stages are often managed using hand-written sample register logbooks, standalone spreadsheets, handwritten test logs, and isolated records, resulting in inefficiencies, duplication of effort, loss of data, limited traceability, and an increased risk of non-conformance with accreditation requirements. The lack of an integrated system restricts management's ability to monitor laboratory performance, equipment utilization, and staff workload in real time. Furthermore, it derails the laboratory management's ability to provide real-time data to the responsible road authorities, road contractors, and the public, so make informed decisions and plan for every road infrastructure project they are involved in.

The aim of this study is to design, develop, and evaluate a simple, customized automated system for PMTL that connects all stages of the laboratory process to improve efficiency, traceability, and compliance. The objective of this research is to review current PMTL practices and explore relevant literature to identify practical automation technologies suitable for adoption into resource-constrained countries. The system developed in this research study is a cost-effective, user-friendly solution tailored for PMTL in PNG. It uses modern web technologies, a MongoDB database, and QR code tracking to simulate real-time laboratory operations. The system ensures a smooth workflow without duplication or data loss, and it was tested using sample data. With appropriate hardware, such as high-performance computers, CPUs, and solid-state drives (SSDs), the system can efficiently support multiple users and faster processing.

Purpose of Automation

In any organization, the decision to automate systems and processes is typically driven by a combination of external and internal pressures aimed at achieving operational efficiency and organizational objectives. External pressures arise from the operating environment and include increasing demand for testing services, higher volumes of daily sample submissions, stringent project deadlines, limited manpower capacity, insufficient laboratory equipment, and the need to comply with continuously evolving standards, policies, and guidelines.

Conversely, internal pressures originate within the organization and are associated with operational inefficiencies, process ineffectiveness, data manipulation risks, bias, human error, time wastage, and elevated operational costs. These challenges are largely attributable to reliance on manual processes and human intervention. Automation is therefore introduced as a strategic response to mitigate internal inefficiencies while simultaneously addressing external demands.

The transition to automation has the potential to significantly enhance laboratory performance; however, it may also introduce new risks and challenges. Consequently, these factors must be carefully evaluated during the planning and design phases of system development. This discussion provides a critical perspective intended to inform stakeholders, including those with limited prior exposure to automation, in preparing for the complexities associated with such technological transformation [12].

METHODOLOGY

Overview

This study employs a systematic review and framework development methodology to investigate and establish an automation model for Pavement Materials Testing Laboratory (PMTL) processes. The approach combines structured literature analysis with conceptual system design to identify, evaluate, and synthesize relevant automation technologies applicable to laboratory operations.

The methodology is aligned with the research objective of developing a practical, scalable, and context-appropriate automation framework that enhances operational efficiency, ensures data integrity, and supports compliance with ISO/IEC 17025:2017 requirements. By integrating theoretical insights with system design principles, the study provides a foundation for transforming conventional PMTL workflows into digitally enabled and quality-assured processes.

Literature Review

Laboratory automation has advanced significantly with the integration of emerging technologies such as robotics [14], artificial intelligence (AI) [6], the Internet of Things (IoT) [3,4], cloud computing [2,5,15], and Laboratory Information Management Systems (LIMS) [8]. These technologies have enabled modern laboratories to streamline operations, enhance data management, and improve overall analytical performance.

Automation facilitates standardized workflows, reduces manual intervention, and ensures consistency in testing procedures. As a result, laboratories benefit from increased operational efficiency, shorter turnaround times, and improved accuracy and reliability of results. These advantages are particularly critical in high-throughput environments, where repeatability and precision are essential for maintaining quality outcomes [1,10,11,12].

Existing studies demonstrate that automation not only improves productivity but also reduces operational costs while strengthening traceability and compliance with quality management standards. Despite these benefits, the level of automation adoption varies across laboratory sectors. PMTLs remain relatively underdeveloped in this regard, lagging behind more technologically advanced fields such as biomedical and chemical laboratories.
Furthermore, the successful implementation of automation requires careful evaluation of laboratory needs, operational constraints, and system suitability prior to deployment [12]. It is equally important to examine the underlying principles of automation and assess their long-term benefits, limitations, and sustainability within the PMTL context.

Benefits and Challenges of Automation

Key Benefits of Automation

The integration of automation technologies in laboratory environments offers several significant advantages that enhance both operational performance and quality outcomes. A primary benefit is **improved traceability**, whereby automated systems enable real-time data capture, storage, and retrieval, facilitating efficient access to records for audits, verification, and reporting purposes.
Automation also contributes to the **reduction of human error** by minimizing manual data entry, calculations, and duplication of records. This leads to more reliable datasets and reduces the likelihood of inconsistencies in laboratory results. In addition, **operational efficiency** is substantially increased through the standardisation and streamlining of workflows, allowing laboratories to operate continuously with minimal interruption and improved throughput.
Another critical advantage is the enhancement of **data quality and reproducibility**. Automated processes ensure consistent execution of testing procedures, thereby improving the reliability and repeatability of results across multiple trials. Furthermore, automation supports **cost reduction** by optimising resource utilisation, minimising material waste, and reducing reliance on labour-intensive processes.
Automation also enables a significant **reduction in turnaround time**, as systems can perform multiple tasks simultaneously and continuously without the limitations associated with manual operations. Lastly, **enhanced safety** is achieved by reducing human exposure to hazardous materials and environments, while incorporating automated monitoring and control systems that improve workplace safety conditions.

Challenges of Automation

Despite the substantial benefits, the adoption of automation in laboratory environments presents several challenges that may affect its long-term sustainability and effectiveness. One of the primary constraints is the **high initial investment cost** associated with acquiring, implementing, and maintaining automated systems. This financial barrier is particularly significant in resource-constrained environments such as PMTLs.
In addition, **continuous capacity development** is required to ensure that laboratory personnel have the necessary technical skills to operate, maintain, and troubleshoot automated systems. This creates an ongoing need for training and upskilling, particularly in areas related to system integration and quality assurance.
System integration and complexity also pose challenges, as automation often involves the integration of multiple technologies, such as LIMS, IoT devices, and cloud-based platforms, which must function cohesively

within existing laboratory workflows. Poor integration can lead to inefficiencies and reduced system performance.
Furthermore, **technological limitations** and infrastructure constraints may restrict the applicability of automation solutions, particularly in laboratories with inadequate digital infrastructure or unreliable power and network systems. The lack of robust implementation strategies and limited understanding of quality assurance requirements can further increase the risk of system failure or non-compliance.
Additionally, inefficiencies in traditional laboratory operations and inadequate infrastructure continue to compromise the quality of pavement materials, contributing to increased road maintenance costs annually. These challenges highlight the necessity for carefully planned, context-specific automation solutions that address both technical and operational constraints [1,10,11,12].

PMTL Needs Assessment and Requirement Analysis

A comprehensive assessment of existing PMTL workflows, as illustrated in ***Figure 1***, was conducted to identify operational inefficiencies and system limitations. This assessment involved a systematic review of key laboratory documents, including management guidelines and policies, standard test methods, operating procedures, and relevant local and international road design standards [16 – 29]. The analysis focused on critical stages of the laboratory workflow, namely: test request submission and billing, sample receipt and registration, test allocation and scheduling, data recording and processing, and result validation and reporting. Based on this evaluation, a gap analysis was undertaken to identify major operational challenges. These include reliance on manual and paper-based data handling, increased risk of transcription errors, limited integration across laboratory functions, delays in reporting and decision-making, and compliance risks in relation to ISO/IEC 17025 requirements. The identified gaps provide a clear basis for defining the need, scope, and functional requirements for implementing an automated PMTL system.

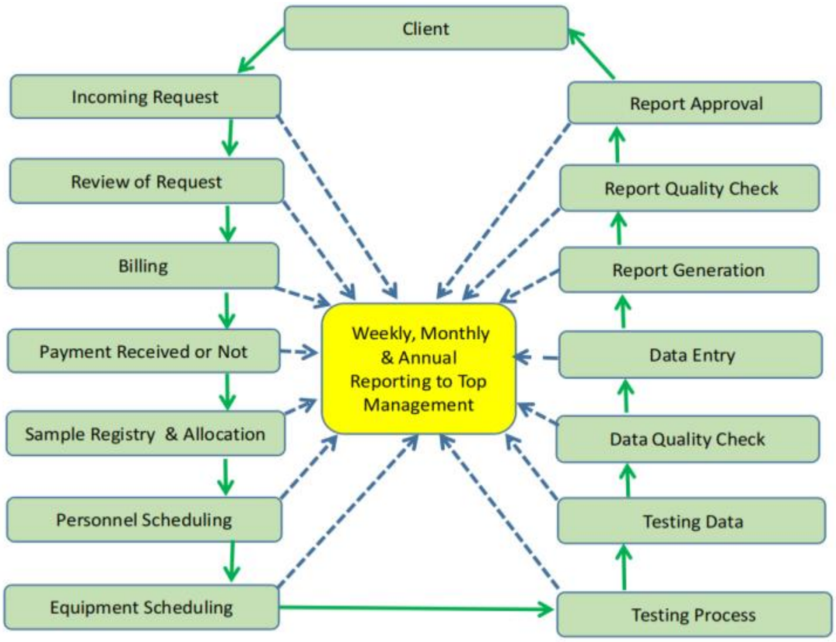

Figure 1: PMTL Manual Process

System Design and Architecture

This phase is based on the findings from the literature review and gap analysis. A conceptual automation system was developed to address the identified challenges in PMTL operations. The systems adopts a systems integration approach, linking all stages of the laboratory workflow through a centralized digital platform, including: Request submission and billing; automated sample registration using R/barcode systems; intelligent test allocation based on resource availability; automated data processing, quality checks, and digital approval; and real-time reporting and client communication. The system is a simple, customized, web-based application developed to streamline and digitize the workflow of laboratory testing processes. It replaces manual paperwork with a semi-digital system while still supporting physical test procedures. This system integrates modern web technologies with Mongo database management and QR code tracking to simulate a real-world laboratory environment.

Design System Components and Their Functions

The Automated System Overview: The automated system is designed in two main user interfaces, as illustrated in ***Figure 2***, the client panel, where clients submit their testing requests along with the bills, and the admin panel, where laboratory staff manage, review, and process those requests and track the progress of the testing process.

Figure 2: Client and Admin Panel.

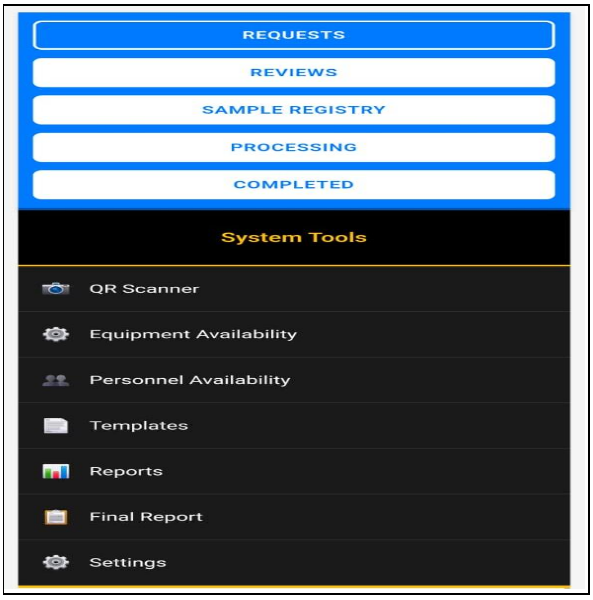

Figure 3: Admin Panel - Laboratory Staff manage, review and process requests

The workflow: The automated system workflow, illustrated in ***Figure 4***, is designed as a sequential and structured lifecycle. Each stage ensures consistent data flow between processes, minimizing the risk of duplication or data loss.

Figure 4: Workflow structured lifecycle

Client Request Module: Within the client request module, users are required to enter their personal and contact details, select the relevant test methods along with the associated total testing fees, and submit a formal request for laboratory testing. The selected test methods are systematically stored in the database and serve as the basis for all subsequent processing stages. This approach ensures that only the requested tests are carried forward and executed within the system, thereby maintaining process accuracy and consistency.

Review Process: This process ensures that only technically feasible and formally approved requests and samples advance to subsequent stages, in accordance with ISO/IEC 17025 requirements, as illustrated in ***Figure 3.***

Review and Approval System: Following submission, each request is routed to the administrative review section within the system. At this stage, the administrator assesses the request in conjunction with the physical sample inspection using predefined evaluation criteria, including the availability of the required test methods, the readiness of laboratory resources (equipment and personnel), specified accuracy requirements, and applicable legal and regulatory obligations.

Sample Registry: Following approval, the request is formally registered as a laboratory sample within the system. At this stage, a unique sample identification number is generated and linked to a barcode for tracking purposes. Relevant equipment and personnel are assigned, and all sample details are systematically recorded in the database. The barcode is then generated and sent for printing to be physically attached to the sample. This stage serves as a critical interface between administrative authorization and the commencement of laboratory testing activities.

Processing Module: The processing module tab is responsible for initiating and managing laboratory testing activities. It displays only the test methods selected by the client, allows laboratory personnel to mark tests as "started," and provides an option to generate and print test forms. Upon initiation, the system automatically produces a printable PDF test form based on predefined templates. These forms are used within the laboratory to manually record data obtained during the execution of physical test procedures.

QR and Bar Code Integration: A key feature of the system is the integration of QR and bar codes within test forms and laboratory report PDFs. When a standardized test form is generated, a QR and a bar code are embedded into the document containing structured data such as the Sample ID, Test Code, and Request ID. This ensures that each printed form is uniquely identifiable and traceable. The use of QR and bar codes enables rapid sample tracking and significantly reduces manual errors, particularly when managing multiple samples simultaneously.

Completion and Registration of Test Forms: Upon completion of laboratory testing and the return of the physical test form, the system provides a "Completed" tab module where users input the Sample ID and Test Code to register the test outcome. The system then updates the test status to "Completed," ensuring that completion is recorded only after the actual laboratory work has been finalized. This approach maintains data integrity and allows assigned personnel and equipment to be released and returned to an available state. Future enhancements will include QR code scanning to automate this process and further improve efficiency.

Data Entry and Report Generation: Following the completion and sign-off of the test form, the recorded data are entered into the system through the reporting module. At this stage, the user inputs the test results into the designated reporting template within the system. Once all required data have been entered, the user activates the "Accept" function, which forwards the draft report for quality control review. After successful completion of the quality checks, the authorized signatory applies a digital approval to finalize the report. The system then enables the reporting function, generating the final laboratory report in PDF format. The report is subsequently stored within the system, sent to the printer, and automatically issued to the client along with a standard notification confirming report release.

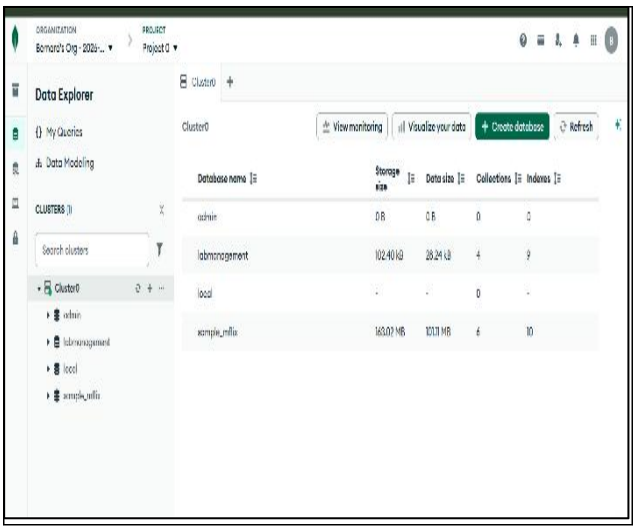

Figure 5: Mongo Database

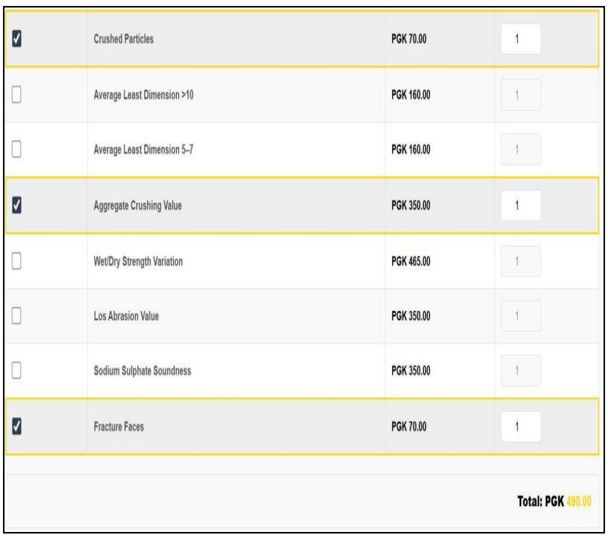

Figure 6: Test request and Invoicing tab

Database Integration (MongoDB): The system uses MongoDB, as illustrated in Figure 5, as its primary database platform. This replaces the earlier JSON-based storage approach and provides enhanced data persistence, structured document-oriented storage, efficient querying and updating capabilities, and robust support for multi-user environments. Key data entities, including test requests, sample records, and test statuses, are stored as documents, thereby improving the system's scalability, reliability, and maintainability.

Validation

A scalable database system was designed and developed using MongoDB, as illustrated in Figure 5, integrating system analysis with database development principles." The proposed system was validated through the use of representative sample data inputs to simulate typical laboratory operations. The results demonstrate that the automated system is functionally feasible and capable of supporting core PMTL processes. The system is designed to operate within a centralized computing environment, enabling efficient data storage and real-time processing of information generated by multiple users within the PMTL setting. This configuration supports improved data accessibility, processing speed, and overall system performance. The validation process focused on assessing system functionality, data integrity, workflow integration, and operational efficiency to ensure alignment with laboratory requirements and the intended use.

Submission of Request: The client selects the test method in the front-end panel, and the system generates the invoice as illustrated in ***Figure 6,*** according to the test methods selected.

Review of Request: In this phase, in the Review Request tab, ***Figure** 7*, the user reviews the request using the checklist items in accordance with ISO 17025 against the actual sample received. Once all checklist items are approved, the sample is registered.

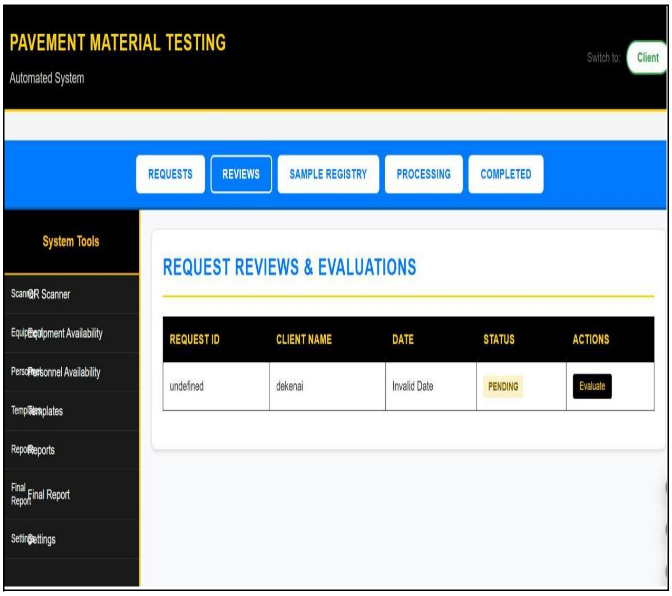

Figure 7: Review of Request tab

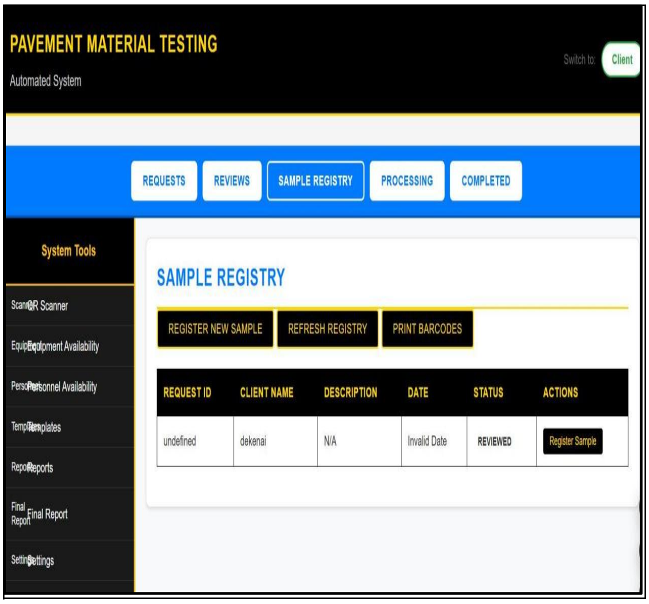

Figure 8: Sample Registry tab

Sample Regareter: In this stage, the sample is registered in the sample registry tab illustrated in ***Figure 8***; a unique ID and a barcode are generated and sent to the printer to be printed. The standardized test forms are also printed for each test method as per the request, and the same barcode is pasted on the test forms to avoid data loss and duplications during the testing process.

Personal and Equipment Scheduling: This stage comes under the sample registry tab. The available equipment and personnel are indicated for the admin user to assign the samples.

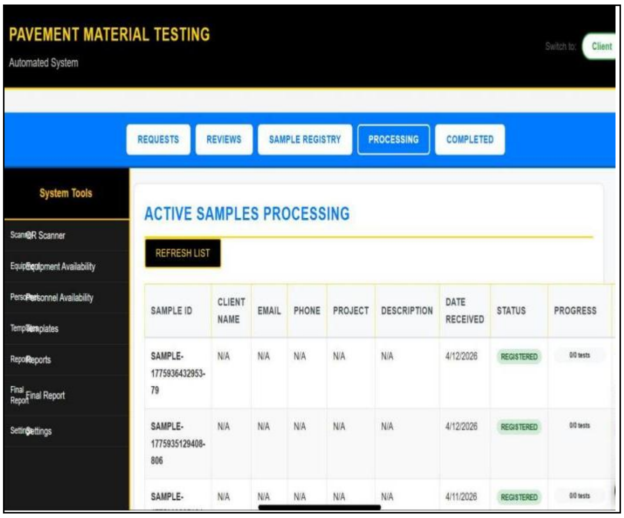

Figure 9 - Sample Processing tab

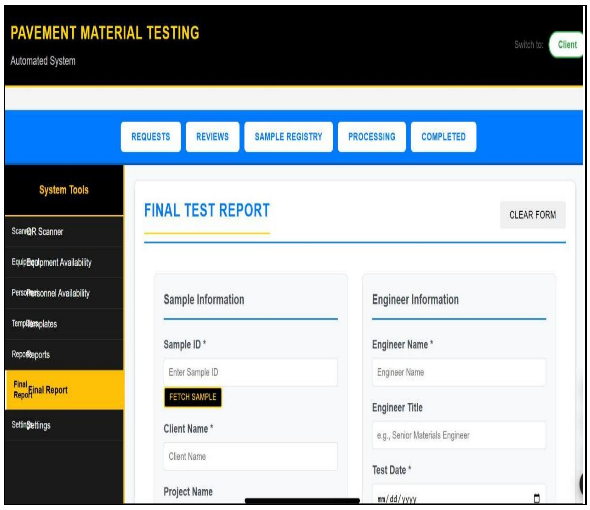

Figure 10: Test Report Generation tab

Sample Processing: In this stage, the test forms and samples have been barcoded and allocated to the personnel assigned to conduct the tests. They now appear in the Sample Processing tab in ***Figure 9*** in the system, as in progress.

Test Reporting: In this stage, the test form is returned, and the data is entered in the Reporting tab in ***Figure 10 to*** generate the pavement test report, which will be sent to quality control for approval in the next stage.

Comparison Between Commercial LIMS and the Developed PMTL Automated System

A Laboratory Information Management System (LIMS), such as those described by Autoscribe Informatics, is a comprehensive platform designed to manage laboratory data, workflows, and compliance requirements across the entire laboratory lifecycle. It provides a centralized system that standardizes workflows, integrates instruments, enforces procedures, and supports regulatory compliance such as ISO/IEC 17025.
In contrast, the automated PMTL system developed in this study is a **lightweight, modular, and context-specific solution** designed specifically for construction materials testing laboratories operating in resource-constrained environments such as Papua New Guinea.

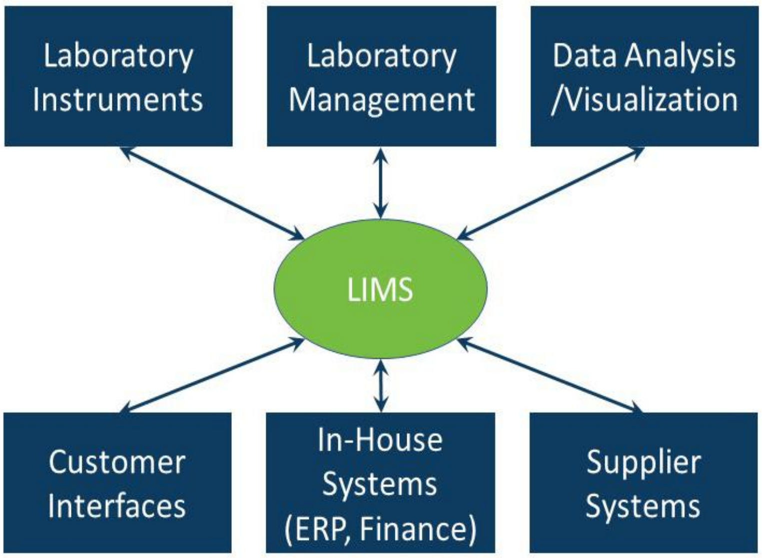

Figure 11: Commercial LIMS

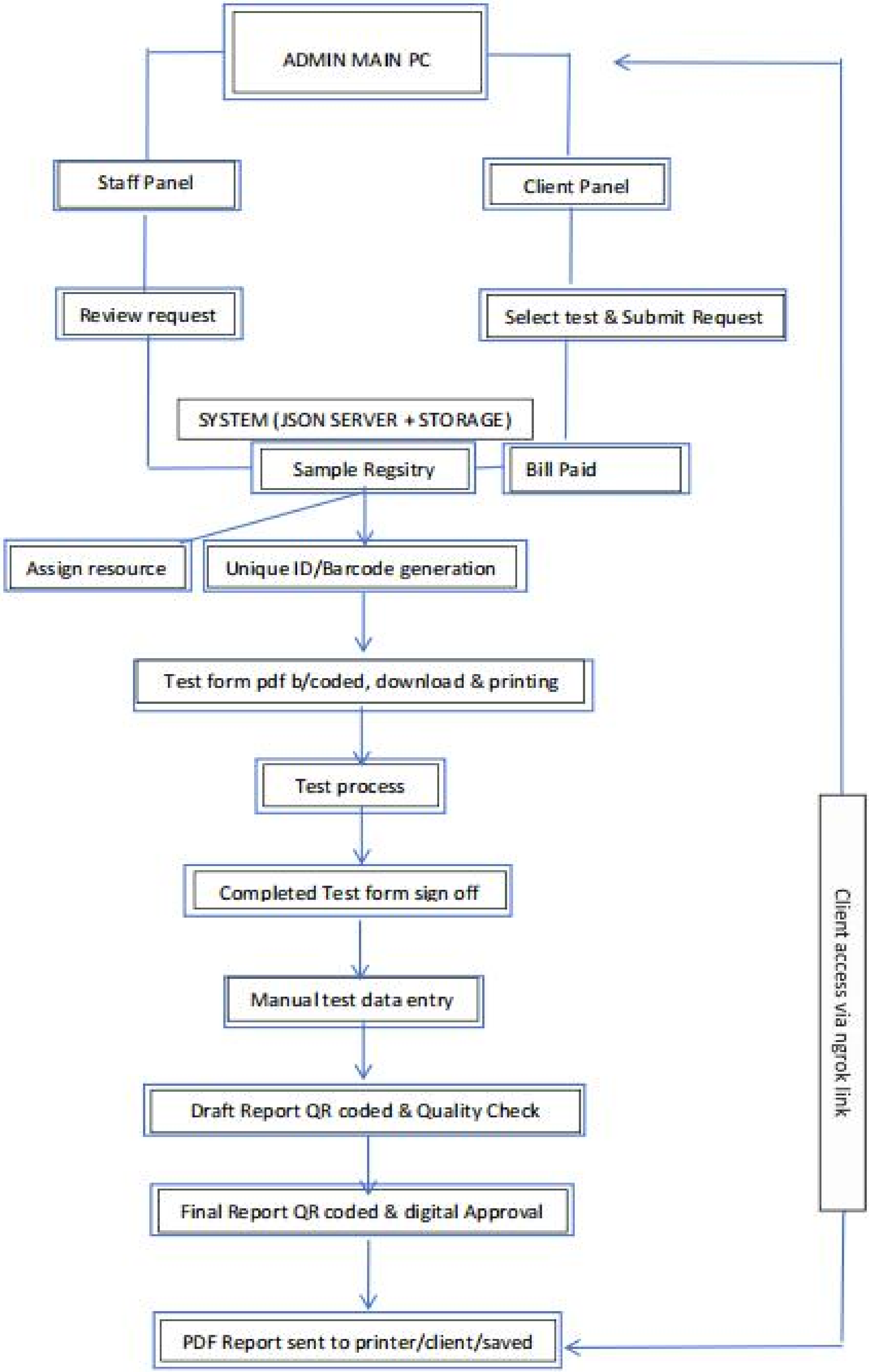

Figure 12: PMTL Automated System

Functional Comparison

Aspect	Commercial LIMS (Autoscribe Model)	Developed PMTL System
System Scope	Fully integrated, enterprise-level system covering all laboratory and business functions	Focused, end-to-end workflow system tailored to PMTL operations
Workflow Management	Highly configurable workflows with enforcement of SOPs and automation across all lab activities	Sequential, structured workflow designed specifically for PMTL processes (request → testing → reporting)
Sample Management	Advanced sample lifecycle tracking with chain-of-custody and storage management	Sample registration with unique ID and barcode/QR tracking for traceability
Instrument Integration	Direct integration with laboratory instruments for automated data capture	No direct instrument integration; relies on manual data capture from physical testing
Data Management	Centralized database with large-scale data analytics, reporting, and historical data retrieval	MongoDB-based document storage for structured, scalable, and efficient data handling
Automation Level	High level of automation, including data capture, analysis, reporting, and decision support	Semi-automated system combining a digital workflow with manual laboratory testing
Compliance Support	Built-in compliance with ISO 17025, FDA, GLP, and audit trails	Designed to align with ISO/IEC 17025 principles but without full regulatory automation features
Integration Capability	Integration with ERP, finance, inventory, and external systems	Standalone system with limited external integration
User Management	Advanced role-based access control and multi-department support	Basic role-based interaction (client, admin, lab staff)
Reporting	Automated generation of certificates, analytics, and management reports	Automated PDF report generation with a digital approval workflow

Table 1: Functional comparison between PMTL system and Commercial LIMS

Implementation and Practical Considerations

Aspect	Commercial LIMS	Developed PMTL System
Cost	High initial investment and licensing costs	Low-cost solution using web technologies
Infrastructure Requirement	Requires strong IT infrastructure and system integration capability	Minimal infrastructure requirements; suitable for developing environments
Ease of Implementation	Complex setup, configuration, and validation processes	Simple, user-friendly, and quick to deploy
Technical Expertise	Requires trained IT personnel and LIMS specialists	Can be managed with basic technical knowledge
Scalability	Highly scalable across multiple laboratories and organizations	Scalable within the PMTL scope but limited for enterprise-level expansion
Sustainability	Requires ongoing vendor support, licensing, and upgrades	Designed for sustainability in low-resource environments

Table 2: Comparison of Implementation and Practical Consideration

Key Analytical Differences

The comparison reveals that commercial LIMS solutions are comprehensive, highly integrated, and compliance-driven systems, designed for large-scale laboratories with sufficient financial and technical capacity. They provide extensive functionality, including instrument integration, enterprise connectivity, and advanced data analytics, making them ideal for highly regulated environments.
However, these systems are often costly, complex, and resource-intensive, which limits their applicability in developing countries and smaller laboratories.

In contrast, the PMTL system developed in this study adopts a pragmatic, context-driven approach, specifically designed to address critical operational gaps inherent in manual laboratory processes. The system emphasizes workflow standardization, enhanced sample traceability through QR code and barcode integration, reduction in turnaround time, minimization of human error, and improvement in overall data integrity. Rather than replicating the full functionality of a conventional LIMS, the system selectively incorporates essential automation features that deliver maximum operational impact while maintaining minimal complexity.

Conclusion of Comparison

The findings indicate that while commercial LIMS platforms provide a gold standard solution for laboratory automation, they are not always suitable for PMTL environments in developing countries due to cost, infrastructure, and sustainability constraints. The developed PMTL system represents a fit-for-purpose alternative, offering a balance between automation and practicality. It achieves core LIMS objectives—such as improved efficiency, traceability, and data reliability—while remaining affordable, adaptable, and easier to implement. Therefore, the study demonstrates that contextualized, simplified automation systems can effectively bridge the gap between manual processes and full-scale LIMS, providing a viable pathway toward digital transformation in resource-limited laboratory environments.

CASE STUDY

Overview

The case study was conducted to collect the views of people working in and involved in PMTL in PNG. Specific structured the survey questionnaire was administered to collect data to support the automation of PMTL in addressing the research gap in this study,. In this case study survey questionnaires were administered to two different groups: six major publicly accredited PMTL and the seven major road contractors who are involved in road design and construction in PNG. The aim of this survey is to collect views from people about laboratory automation and identify the challenges people experience when working with and dealing with current PMTL practices in PNG.

Pavement Material Testing Laboratory Survey

A case study was conducted to evaluate the current operational challenges and readiness for automation within PMTLs in PNG. Two sets of structured questionnaires were administered across six public, commercial, and accredited PMTLs. The questionnaires were specifically targeted at laboratory managers and laboratory technicians who are directly involved in daily laboratory operations.
Responses obtained from laboratory managers indicate a generally positive perception of automation. Approximately 70% of the managers expressed support for the adoption of automation in PMTL processes, while 30% preferred to maintain existing manual systems. Notably, all surveyed laboratories currently operate under manual conditions. In a related assessment, 80% of the managers agreed that automation would improve laboratory processes, whereas 20% disagreed. The primary concerns raised by those opposing automation were associated with reliance on manually operated equipment, limited financial resources, inadequate infrastructure, and the lack of accessible automation technologies within the country.
A more detailed operational assessment was conducted using questionnaires administered to 60 laboratory technicians, with ten (10) respondents selected from each PMTL. The questionnaire was structured around six key stages of the laboratory process, namely test request handling, sample registration, personnel and

equipment scheduling, testing procedures, data management, and compliance with ISO/IEC 17025 requirements. The responses were analysed using a quantitative approach to identify the frequency and distribution of operational challenges across these stages.

The findings indicate that challenges are prevalent across all stages of PMTL operations. At the request handling stage, all respondents reported difficulties in receiving and processing requests, and the majority also experienced issues related to procedural consistency and documentation. During sample registration, a significant proportion of technicians reported challenges in registering samples, capturing client information, and maintaining sample traceability. In the stage involving the coordination of samples, personnel, and equipment, most respondents indicated difficulties in scheduling personnel for testing activities, allocating equipment, and managing equipment calibration. Testing procedures were found to be entirely manual, with all respondents confirming the manual execution of tests and quality checks, and a substantial proportion reporting issues in maintaining consistent quality control.

Data management practices were also largely manual, with all respondents verifying data manually, and a considerable number reporting challenges in data recording and management. Similarly, compliance activities, including audits and quality checks, were performed manually by all respondents, and many indicated difficulties in effectively conducting compliance assessments. Overall, the results demonstrate that operational challenges are widespread across all six stages of the PMTL workflow. Approximately 80% of laboratory personnel reported significant issues affecting their daily activities, while the remaining 20% indicated only minor challenges or a preference for maintaining existing manual processes. These findings are consistent with the workflow analysis presented in Figure 1, which illustrates the structure of the current manual laboratory system. The case study highlights the limitations of manual PMTL operations and reinforces the need for an integrated automation framework to improve efficiency, enhance traceability, and support compliance with quality standards.

Road Contractor Survey

In this phase, structured questionnaires were administered to road contractors involved in the design and construction of road infrastructure projects in Papua New Guinea (PNG). The primary objective was to assess how laboratory test data influences project delivery timelines and pavement quality, and to evaluate contractor perspectives on the adoption of Public Materials Testing Laboratory (PMTL) automation. The survey findings indicate that turnaround time (TAT) for laboratory reports remains a critical concern. A substantial majority of contractors (80%) reported consistent delays in the release of laboratory results, often extending over several weeks. These delays were identified as having a direct negative impact on construction scheduling, decision-making processes, and overall project delivery. In contrast, 20% of respondents indicated that they did not experience significant issues with turnaround time. In terms of data integrity and quality, 70% of contractors reported frequent challenges, including inaccurate results, incomplete datasets, and test outputs that did not meet specified requirements. These deficiencies undermine confidence in laboratory outputs and can adversely affect the quality of pavement design and construction. The remaining 30% of respondents expressed neutral views or reported only minor issues related to data quality. With respect to automation, there is strong support among contractors for the modernization of PMTL processes. Approximately 80% of respondents endorsed automation, highlighting its potential to improve turnaround time, enhance data accuracy, and increase overall operational efficiency. Conversely, 20% of contractors expressed a preference for maintaining manual systems. These respondents emphasized the use of legally binding agreements with laboratories to ensure timely delivery of results and adherence to contractual obligations.

Despite this preference, it was widely acknowledged that manual processes inherently introduce risks associated with human error, data manipulation, and reduced impartiality. As such, automation is viewed as a more reliable and transparent approach to addressing these systemic issues within laboratory operations.

Overall Case Study Outcomes

The combined findings from both PMTL personnel and road contractors demonstrate a clear inclination toward the adoption of automated systems. From the laboratory perspective, 80% of respondents supported automation as a means to improve operational efficiency, reduce turnaround time, and minimize errors. The remaining 20% expressed reservations, primarily due to limitations in funding, resource availability, and concerns regarding the long-term sustainability of automation technologies. Similarly, 80% of road contractors supported automation, citing improvements in data reliability and project delivery performance as key drivers. The remaining 20% preferred manual or hybrid approaches, relying on contractual enforcement mechanisms to ensure compliance with reporting timelines and service expectations.

Conclusion

Overall, the findings of this case study demonstrate that data integrity and quality are significantly compromised in manual laboratory environments due to the inherent risks associated with human involvement. These risks include errors, inconsistencies, bias, and potential data manipulation. Consequently, the implementation of an automated PMTL system is strongly recommended as a strategic intervention to enhance transparency, improve data reliability, and optimize laboratory process efficiency, thereby supporting better project delivery outcomes in the road construction sector.

FINDINGS AND DISCUSSIONS

Overview

The findings of this study present a structured evaluation of the literature, existing manual laboratory processes, and applicable automation technologies relevant to Public Materials Testing Laboratories (PMTL). The analysis focused on identifying practical, cost-effective, and user-friendly technological solutions that can be adapted to resource-constrained environments. Particular emphasis was placed on technologies that can be customized to suit PMTL operations in developing countries while maintaining compliance with ISO/IEC 17025:2017. Through a systematic assessment, key technological enablers, operational inefficiencies, and integration opportunities were identified. The results demonstrate that end-to-end automation has significant potential to enhance operational efficiency, improve data accuracy, and strengthen compliance with quality management requirements.

Potential Automation Technologies for PMTL

A range of automation technologies applicable to PMTL operations was identified and evaluated using a structured assessment framework. These technologies include Laboratory Information Management Systems (LIMS), Internet of Things (IoT)-enabled laboratory equipment, Artificial Intelligence (AI) for data validation and analysis, barcode and QR code-based sample tracking systems, and cloud-based data management platforms. Each technology was assessed against criteria such as applicability to laboratory workflows, alignment with ISO/IEC 17025:2017 requirements, implementation feasibility, cost-effectiveness, scalability, flexibility, and integration capability with existing systems. The evaluation indicates that while advanced systems such as LIMS offer comprehensive functionality, their adoption in developing contexts is often constrained by high costs and infrastructure requirements. In contrast, modular and web-based solutions incorporating QR code tracking and cloud data management present more practical and scalable alternatives for PMTL environments.

PMTL Process Gaps and Challenges

The study identified a critical research gap in the absence of a fully integrated, end-to-end automated system tailored specifically for PMTL operations. Existing solutions do not adequately link essential laboratory functions, including test request initiation, sample receipt and registration, personnel and equipment scheduling, real-time monitoring, data processing, and report generation within a unified workflow.

The analysis of current manual PMTL processes revealed several operational challenges. These include process fragmentation leading to delays, heavy reliance on manual labour resulting in increased error rates, and persistent issues related to data integrity and traceability. The absence of real-time monitoring further limits operational visibility and responsiveness. Additionally, the use of paper-based records contributes to data loss, miscommunication, and inefficiencies in personnel and equipment allocation. These factors collectively reduce overall laboratory efficiency and increase risks related to safety, environmental management, and compliance with accreditation requirements.

Challenges in Automation Adoption

Despite the clear advantages of automation, several barriers to implementation were identified. These include the high initial cost of acquiring automation technologies, limited infrastructure to support digital systems, and the lack of consistent funding and resource allocation. Furthermore, there is a shortage of local technical expertise and limited access to advanced technologies in developing countries. Sustainability of implemented systems remains a concern, particularly in the absence of ongoing capacity development and technical support. Limited awareness and understanding of automation technologies among stakeholders also pose challenges to adoption and effective utilization.

Benefits of Automation

The findings highlight multiple benefits associated with the adoption of automation in PMTL operations. Automation significantly improves data traceability by enabling instant retrieval of records for audits, verification, and reporting purposes. It reduces human error by minimizing manual data entry, calculations, and duplication of records. Operational efficiency is enhanced through streamlined and standardized workflows, allowing continuous processing and faster turnaround of laboratory results. Automation also improves data quality and reproducibility by ensuring consistency in testing and reporting processes.

In addition, automation contributes to cost reduction by minimizing material wastage and optimizing resource utilization, while enabling simultaneous execution of multiple tasks. Turnaround time is significantly reduced due to continuous system operation and elimination of manual bottlenecks. Enhanced safety is another critical benefit, as automation reduces human exposure to hazardous materials and enables the implementation of digital safety monitoring systems within laboratory environments.

Case Study Findings

The case study results further reinforce the need for automation in PMTL operations. The PMTL survey indicated that 80% of laboratory respondents support automation to improve efficiency, reduce turnaround time, and minimize errors. The remaining 20% expressed concerns primarily related to the lack of funding and resources required for implementation and sustainability.

Similarly, the contractor survey revealed that 80% of respondents support automation, recognizing its potential to improve turnaround time and enhance data accuracy. However, 20% preferred to retain manual processes, relying on contractual agreements with laboratories to ensure timely delivery of results. Despite this preference, the findings indicate that manual systems are inherently prone to errors and inconsistencies, thereby affecting data reliability and project outcomes.

Comparison of Manual and Automated PMTL Processes

The comparison between manual and automated laboratory processes demonstrates significant performance differences. Manual practices constrain laboratory efficiency due to delays, inconsistencies, and increased error rates, ultimately compromising data integrity and compliance with standards. These limitations also increase risks related to impartiality and the reliability of test results.

In contrast, automated systems enhance laboratory performance by standardizing workflows, improving traceability, and ensuring secure data management. These improvements result in the generation of accurate and reliable data, which is critical for informed decision-making and for the design and construction of durable pavement structures. Automation also supports better resource management and overall operational effectiveness.

Comparison of Commercial LIMS and PMTL System

The findings indicate that although commercial LIMS platforms represent the benchmark for laboratory automation, their adoption in PMTL environments within developing countries is constrained by cost, infrastructure, and sustainability limitations. The PMTL system developed in this study provides a fit-for-purpose alternative by balancing automation with practical implementation. It achieves key LIMS objectives, including improved efficiency, traceability, and data reliability, while remaining affordable, adaptable, and easier to deploy. Accordingly, the study demonstrates that simplified, context-driven automation can effectively bridge the gap between manual processes and full-scale LIMS, offering a viable pathway for digital transformation in resource-constrained laboratory environments.

Discussion

The findings confirm that human involvement in laboratory processes introduces inherent risks to data integrity and quality, primarily due to unintentional errors, inconsistencies, and subjective influences. While human expertise remains essential, excessive reliance on manual processes increases variability and potential bias in testing, recording, and reporting activities. Automation provides a structured solution to these challenges by enforcing standardized procedures, maintaining secure and traceable records, and minimizing opportunities for data manipulation.

However, a balanced approach that integrates automation with appropriate human oversight is necessary to ensure technical validity and compliance with quality management standards. The customized web-based system developed in this study demonstrates a practical approach to PMTL automation. The system digitizes laboratory workflows, replacing paper-based processes with a semi-automated solution while maintaining physical testing procedures. It integrates web technologies, database management systems, and QR code-based tracking to replicate real-world laboratory operations.

The study also highlights that high-end automation technologies, such as full-scale LIMS, may not be suitable for resource-constrained environments due to their high cost and complexity. Instead, the proposed system offers a more feasible alternative by providing a scalable, cost-effective, and user-friendly solution tailored to the needs of developing countries. Its implementation has the potential to significantly improve laboratory performance, enhance data reliability, and support timely decision-making in road design and construction projects in PNG.

CONCLUSIONS

This study has both conceptually and empirically validated an end-to-end automated Pavement Materials Testing Laboratory (PMTL) system tailored to the Papua New Guinea (PNG) context. The proposed system effectively addresses critical operational deficiencies, including limitations in traceability, inefficiencies in workflow execution, suboptimal resource utilization, and challenges in maintaining compliance with accreditation requirements. The findings demonstrate that integrating digital technologies into traditional laboratory environments can significantly enhance overall performance and reliability.

By leveraging web-based platforms, structured database management, and QR code technologies, the system establishes a cohesive link between physical laboratory activities and digital data management processes. This integration ensures improved data integrity, streamlined operations, and enhanced transparency, while maintaining alignment with ISO/IEC 17025 principles of quality and impartiality. The results highlight the practical applicability of the system in real-world laboratory settings and its capacity to support consistent, high-quality outputs.

Furthermore, the implementation of the automated PMTL system presents a scalable and sustainable approach to laboratory management, with direct implications for improving the quality and durability of pavement infrastructure. Future enhancements, including real-time QR code scanning and direct digital integration with laboratory equipment, offer the potential to achieve full automation of data capture and report generation. Such advancements would further strengthen system efficiency, reduce human intervention, and reinforce the reliability of laboratory outputs.

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