Automation of Pavement Material Testing Laboratory Process: Review

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ABSTRACT

Pavement Materials Testing Laboratories (PMTLs) play a critical role in ensuring that pavement materials meet the required specifications to sustain traffic loads and achieve design standards. This study investigates the potential for transforming PMTL operations through the adoption of automation technologies, with a particular focus on developing-country contexts such as Papua New Guinea (PNG). A systematic review of the literature published up to 2025 was conducted using targeted keyword-search strategies to identify relevant advances in laboratory automation across multiple sectors. The review highlights significant progress driven by the integration of artificial intelligence (AI), the Internet of Things (IoT), robotics, and Laboratory Information Management Systems (LIMS). However, findings indicate that PMTLs remain largely dependent on manual processes, limiting efficiency, traceability, and data reliability. To complement the literature review, a case study was undertaken using structured questionnaires distributed to laboratory personnel across six PMTLs and to representatives from seven major road construction companies in PNG. The responses indicate strong support for the adoption of automation to improve laboratory operations. The study identifies a critical research gap in the absence of an integrated, end-to-end automated system capable of linking test requests, sample management, personnel allocation, and equipment utilisation within a unified PMTL framework. While the benefits of automation are evident, challenges related to sustainability, including funding constraints and limited resource capacity, remain significant barriers to implementation. This research contributes to the development of a conceptual foundation for PMTL automation, highlighting the need for scalable, context-specific solutions to enhance quality assurance and operational performance.

Keywords: Laboratory Automation, LIMS, PMT, Laboratory Quality Assurance, ISO/IEC 17025:2017

INTRODUCTION

The performance and durability of road infrastructure depend on the quality and compliance of the construction materials. PMTLs play a critical role in verifying that these materials meet the required engineering specifications and performance standards [17]. Reliable and timely laboratory testing is therefore essential to ensure that pavement systems can withstand increasing traffic demands and achieve design expectations [13],[17]. However, in many developing countries, including PNG, PMTL operations remain largely manual, limiting efficiency, traceability, and data reliability.

Current PMTL practices are characterised by fragmented workflows, limited system integration, and inadequate real-time monitoring of laboratory activities and equipment. These challenges are further compounded by human error, poor data management, and weak sample traceability. As a result, laboratories experience delays in reporting, reduced confidence in test results, and inefficient use of resources, ultimately affecting infrastructure quality and project delivery. Advancements in digital technologies, including AI, the IoT, robotics, and LIMS, have significantly improved laboratory operations in other sectors [11],[12]. These technologies enable automated data capture, real-time monitoring, and integrated workflows, leading to improved accuracy, consistency, and efficiency [1]. Despite these benefits, their adoption in PMTLs remains limited, particularly in resource-constrained environments. This limited adoption is largely due to constraints such as reliance on legacy systems, inadequate infrastructure, financial limitations, and a lack of technical expertise. In addition, concerns

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regarding long-term sustainability, including system maintenance and workforce capacity, continue to hinder implementation. Consequently, many PMTLs are unable to fully benefit from digital transformation, and inefficiencies persist in key operational processes. Although automation has been widely studied in other laboratory domains, there is limited research on its integrated application within PMTLs. In particular, there is a lack of end-to-end systems capable of linking all laboratory functions within a unified framework. Addressing this gap is essential for improving workflow integration and ensuring compliance with quality management standards such as ISO/IEC 17025:2017 [16]. This study therefore investigates the potential to transform PMTL operations through the adoption of integrated automation technologies. A systematic literature review is conducted to identify relevant advancements, supported by a case study involving laboratory personnel and construction stakeholders in PNG. The aim is to develop a conceptual, scalable, and context-specific automation framework that enhances efficiency, improves data integrity and traceability, and supports reliable testing outcomes. Ultimately, this contributes to stronger quality assurance and more durable road infrastructure systems.

LITERATURE REVIEW

Overview of the Literature Review

The development of a user-friendly, scalable, and cost-effective automated laboratory system, particularly in resource-constrained environments, requires a clear understanding of existing technologies and their practical use. This review examines current advances in laboratory automation and evaluates their relevance to PMTLs. The focus is on key elements such as system integration, data management, and process optimisation, with consideration of compliance requirements under ISO/IEC 17025:2017 [7],[9]. The review also identifies common benefits and implementation challenges. This provides a basis for selecting appropriate technologies that suit the operational and financial constraints of PMTLs.

Applications of Automation in Laboratory Systems

Automation technologies are widely used in laboratory and industrial settings. Their application has improved efficiency, accuracy, and overall performance.

The **Internet of Things (IoT)** enables real-time monitoring and control through connected instruments and sensors. It supports automated equipment operation, environmental monitoring, and remote access to systems [3],[4],[5]. **Artificial Intelligence (AI)** and **machine learning (ML)** improve data analysis by detecting patterns and trends in large datasets. These tools support faster decision-making and more reliable interpretation of results [6]. **Robotic Process Automation (RPA)** is used to handle repetitive and rule-based tasks such as data entry, sample logging, and report generation. This reduces the manual workload and improves consistency [10],[12]. **Information technology (IT)**-based optimization systems improve workflow efficiency and reduce turnaround time. These systems are particularly useful in high-demand laboratory environments [15],[2]. **Cloud computing** provides flexible and secure platforms for storing and processing laboratory data. It also supports system integration and allows laboratories to scale their operations as needed [2],[5]. **Laboratory Information Management Systems (LIMS)** act as the central platform for managing laboratory activities. LIMS supports sample tracking, workflow control, equipment monitoring, data analysis, and reporting, while also improving compliance with regulatory standards [1],[8].

Impact of Automation on Quality Assurance

Quality assurance (QA) ensures that laboratory processes and outputs meet the required standards. In traditional laboratories, QA depends heavily on manual checks and supervision. This approach can lead to delays and inconsistencies. Automation improves QA by embedding control mechanisms directly into laboratory processes [7],[9]. Systems can monitor activities in real time, including sample handling and data recording. This allows immediate detection of errors or non-conformities. As a result, laboratory outputs become more consistent and reliable. Automation also reduces dependence on manual oversight and strengthens overall process control. In road construction and engineering applications, improved QA supports better decision-making and contributes to higher-quality road infrastructure outcomes.

Automation in Relation to ISO/IEC 17025:2017 Requirements

Automation supports compliance with ISO/IEC 17025:2017 by improving control, consistency, and traceability.

across laboratory operations. In document control, automated systems ensure that only current and approved versions are used. Version control and approval workflows reduce the risk of outdated documents. Equipment management is also improved. Systems can schedule calibration, track maintenance, and issue alerts when equipment is due for servicing. This helps prevent the use of non-compliant equipment. Automation enhances data integrity by enabling secure, paperless data handling. It reduces transcription errors and protects data from unauthorized access. Personnel competency can be managed more effectively through digital records of training, certification, and authorization. This ensures that only qualified staff perform specific tasks. Automation also supports method validation through structured workflows and consistent data capture. In addition, nonconforming work can be identified quickly through system alerts, allowing prompt corrective action. Overall, automation strengthens the laboratory quality management system and supports sustained compliance with ISO/IEC 17025:2017 [16].

Automation Benefits of Laboratory Automation

Automation improves laboratory performance in several ways. It enhances traceability by providing real-time access to data. It also reduces human error by limiting manual data handling. Workflows become more efficient and consistent through standardization. This leads to improved data quality and reproducibility of results. Automation can reduce operational costs by improving resource utilisation and minimizing waste. It also shortens turnaround time, as systems can operate continuously and perform multiple tasks simultaneously. In addition, automation improves safety by reducing human exposure to hazardous environments and enabling better monitoring of laboratory conditions.

Challenges of Automation

Despite its advantages, automation presents several challenges, especially in developing or resource-limited environments. High initial costs and ongoing maintenance can limit adoption. Skilled personnel are required to operate and maintain automated systems, making training essential. System integration can also be complex. Different technologies and platforms must work together effectively, which may be difficult to achieve. Infrastructure limitations, such as an unreliable power supply or inadequate digital systems, further restrict implementation. In addition, limited experience with automation and quality systems can increase risks during transition. In PMTLs, these challenges are often more pronounced due to existing inefficiencies and limited resources. This highlights the need for practical, scalable, and context-specific automation strategies.

METHODOLOGY

Overview of the Methodology

This study adopts a systematic review and framework development approach to investigate and establish an automation model for PMTL processes. The methodology integrates a structured literature analysis with conceptual system design to identify, evaluate, and synthesise appropriate automation technologies applicable to laboratory operations. The approach is guided by the objective of developing a practical, scalable, and cost-effective automation framework tailored to resource-constrained environments. Emphasis is placed on enhancing laboratory efficiency, improving data integrity, and ensuring compliance with ISO/IEC 17025:2017 requirements. The methodology further incorporates an applied component through a case-based assessment to validate the relevance of the proposed framework within a real PMTL context.

PMTL Needs Assessment and Requirement Analysis

A comprehensive assessment of existing Pavement Materials Testing Laboratory (PMTL) workflows was conducted to identify operational inefficiencies, system limitations, and areas requiring improvement. The current laboratory processes, as illustrated in Figure 1, were systematically analysed across key functional stages,

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including request submission and billing, sample receipt and registration, test allocation and scheduling, data recording and processing, and result validation and reporting. The assessment revealed that PMTL operations remain predominantly reliant on manual and paper-based processes. This reliance contributes to fragmented workflows, limited integration between laboratory functions, and inefficiencies in data management and process coordination. Based on these observations, a gap analysis was undertaken to evaluate the discrepancies between existing practices and the requirements of an automated laboratory system. The analysis identified several critical challenges, including a strong dependence on manual data handling and record-keeping, a high susceptibility to transcription and calculation errors, and a lack of integration across laboratory systems and processes. In addition, delays in data processing, reporting, and decision-making were observed, along with an increased risk of non-compliance with ISO/IEC 17025:2017 requirements. These findings established the functional and technical requirements necessary for automation and provided a foundation for the design and development of an integrated PMTL automation framework. Furthermore, the identified gaps informed the selection of appropriate technologies and system components aimed at improving workflow efficiency, enhancing traceability, and strengthening overall laboratory performance.

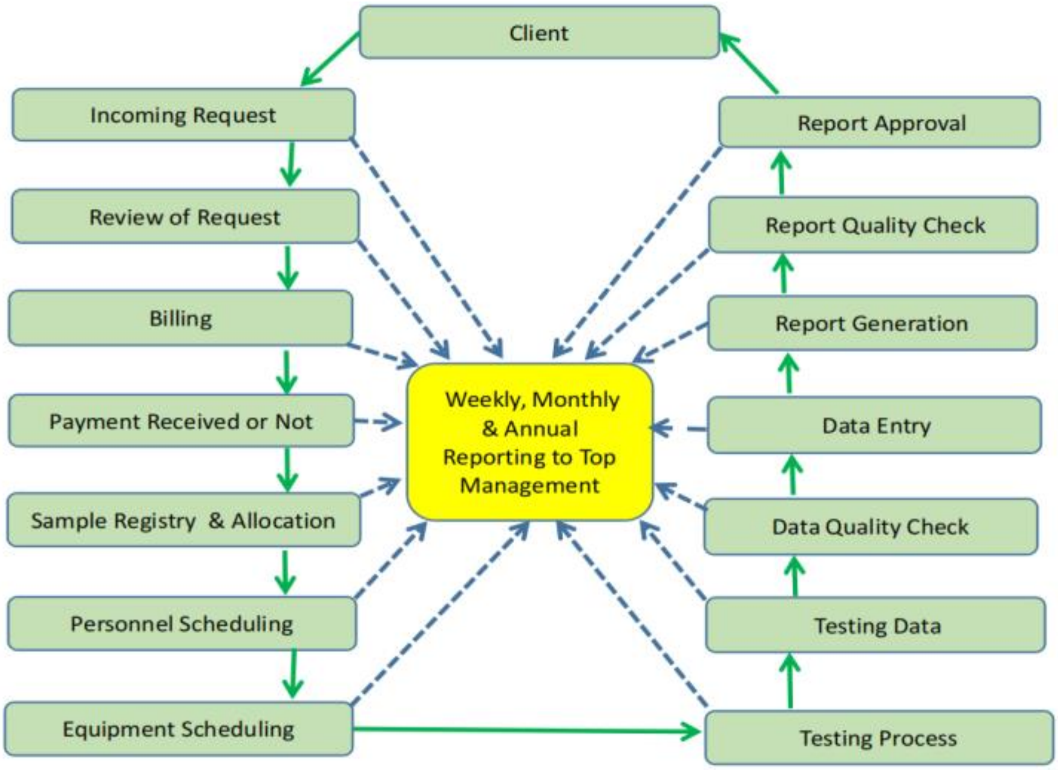

Figure 1:: PMTL Manual Process

System Design and Architecture

Based on the outcomes of the needs assessment and gap analysis, a conceptual PMTL automation system architecture was developed to address identified inefficiencies and operational limitations. The system design adopts a cost-effective, customized, modular, and integrated approach, enabling interoperability between laboratory processes, equipment, and data management platforms. The proposed architecture consists of the following customized core components: **LIMS** serves as the central platform for managing sample registration, workflow coordination, data processing, and reporting. **IoT** Integration enables real-time monitoring of laboratory equipment, environmental conditions, and test processes through connected sensors and devices. **AI and ML support** data validation, anomaly detection, and predictive analysis to improve decision-making and quality assurance. **Automation Interfaces and Robotics** facilitate the execution of repetitive laboratory tasks, reducing manual intervention and improving consistency. **Cloud-Based Infrastructure** provides scalable data storage, secure access, and system interoperability across multiple users and locations. The customized system is designed to enable end-to-end integration of laboratory operations, linking test requests, sample tracking, personnel allocation, equipment utilisation, and result reporting within a unified digital environment. This

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architecture ensures real-time data flow, improved traceability, and enhanced compliance with ISO/IEC 17025:2017 requirements.

Case Study Design and Data Collection

Case Study Approach

A case study was conducted to assess the applicability of the proposed framework in PNG. This approach allows for the collection of real-world data from industry stakeholders and provides insight into current practices and readiness for automation.

Sampling Method and Justification

A purposive sampling method was adopted in this study to select participants with relevant expertise and direct involvement in PMTL operations. This approach is appropriate given the specialised and relatively small target population, where respondents are required to possess adequate technical knowledge of laboratory processes and practices. Furthermore, the study emphasises obtaining in-depth insights rather than achieving broad statistical generalisation, making purposive sampling suitable for capturing informed and experience-based perspectives. The sample comprised laboratory personnel from six PMTLs and representatives from seven major road construction companies. These groups were deliberately selected due to their direct engagement in laboratory testing activities and their reliance on laboratory results for operational and decision-making purposes. Their involvement ensures that the data collected reflect practical realities and industry-specific challenges relevant to PMTL automation.

Questionnaire Design

The questionnaire was developed based on insights obtained from the literature review and the needs assessment. It was structured into five key sections covering current laboratory practices, operational challenges, awareness of automation technologies, perceived benefits and barriers, and readiness for automation. The instrument included both closed-ended and open-ended questions. Closed-ended questions were used to generate quantifiable data for statistical analysis, while open-ended questions allowed respondents to provide detailed insights and elaborate on their experiences and perspectives.

Sample Collection

A total of thirteen (13) questionnaires were distributed to sixty (60) laboratory personnel: ten (10) from each of the six PMTLs. Out of the sixty (60), forty-nine (49) participants had significant issues in the laboratory process; this was evaluated as eleven (11) valid responses received from the 13 questionnaires initially distributed, resulting in a response rate of eighty-five percent (85 %), indicating issues with the laboratory process. The other three (3) questions were issued to seven contractors in PNG; five (5) contractors had issues with the laboratory process. This was then evaluated as two (2) valid responses received from the three (3) questionnaires administered, resulting in a response rate of sixty-seven percent (67%) indicating issues with the PMTL process. The support for Automation was collected from the sixty (60) participants with the six (6) PMTLs; forty-eight (48) supported automation. While six (6) out of the seven (7) contractors agreed to automation. The outcome of the study indicated strong support for automation from both scenarios, with eighty percent (80%) and eighty-five percent (85) respectively. The collected data were screened for completeness and consistency prior to analysis to ensure data quality and reliability, and the results are presented in Table 1. The sample size is considered adequate for an exploratory case study, where the emphasis is on obtaining detailed, context-specific insights rather than statistical generalisation. The relatively high response rates indicate strong participant engagement and contribute to the reliability of the findings. This case study therefore serves as a critical validation component, linking the proposed framework to real-world laboratory conditions and stakeholder expectations.

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Table 1: Case Study Response Summary

Category		No. of people used	Support for Automation
Six PMTL in PNG			
Total Questionnaires	13	60	80%
Response received on the issues.	11	49	
Response rate on issues	85%		
Seven Contractros in PNG			
Total Questionnaires	3	7	85%
Response received on the issues.	2	5	
Response Rate on issues	67%		

Data Analysis Methods

The data obtained from the literature review and case study were analysed using a mixed-methods approach, combining qualitative and descriptive quantitative techniques. Qualitative analysis was applied to interpret responses related to challenges, opportunities, and perceptions of automation. Thematic analysis was used to identify recurring patterns and key issues affecting PMTL operations. Quantitative analysis involved summarising questionnaire responses using descriptive statistics, such as frequencies and percentages, to evaluate the level of support for automation adoption. The integration of these methods enabled a comprehensive evaluation of both theoretical insights and practical perspectives, strengthening the reliability of the study findings.

Framework Development

The development of the PMTL automation framework was informed by a combination of findings derived from the literature review, results obtained from the needs assessment and gap analysis, and insights generated through the case study. These components collectively provided a comprehensive foundation for identifying system requirements and defining the structure of the proposed solution. Based on this integrated analysis, a conceptual framework was designed to consolidate key laboratory functions within a cohesive,automated system environment. The framework enables end-to-end integration of laboratory workflows, facilitating seamless coordination from test request initiation through to final reporting. It incorporates real-time data management capabilities to enhance traceability and ensure continuous monitoring of laboratory activities. In addition, the framework supports the automation of critical laboratory processes, thereby reducing manual intervention and improving operational efficiency. The proposed system is further aligned with the quality management principles outlined in ISO/IEC 17025:2017, ensuring that compliance requirements are embedded within the automated processes. Emphasis is placed on scalability and adaptability, allowing the framework to be effectively implemented in resource-constrained environments while maintaining the flexibility to accommodate future technological advancements and improvements in infrastructure and technical capacity.

Validation of the Proposed Framework

The proposed automation framework was validated using a multi-criteria approach that combined comparative analysis, expert feedback, and a case study-based assessment. Initially, the framework was evaluated through a systematic comparison with existing PMTL practices to determine its effectiveness in addressing identified operational gaps. Particular attention was given to improvements in workflow integration, data management, traceability, and overall process efficiency. To strengthen the validation, the proposed framework was further assessed against established automation practices in other laboratory sectors. This comparative evaluation ensured alignment with proven technological approaches and industry standards, particularly in relation to system integration, real-time data processing, and quality management compliance. In addition, expert feedback was incorporated into the validation process. Domain experts, including laboratory managers and quality professionals familiar with ISO/IEC 17025:2017, reviewed the framework to assess its technical soundness, feasibility, and alignment with practical laboratory requirements. Their input provided critical insights into system functionality, implementation challenges, and potential areas for refinement. A case study-based validation was also undertaken using data collected from PMTL personnel and contractor representatives. The

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responses were analysed to evaluate the level of acceptance, perceived usefulness, and readiness for adopting the proposed system. The findings indicated strong support for automation and confirmed the relevance of the framework in addressing current operational challenges within the PNG context. The integration of these validation methods ensures that the proposed framework is not only theoretically robust but also practically viable. It demonstrates strong alignment with user needs, industry practices, and operational realities, making it suitable for implementation in resource-constrained and underdeveloped-country environments.

FINDINGS AND DISCUSSION

The findings of this study, derived from the review of recent literature published up to 2025, indicate that laboratory automation has significantly transformed operational practices across multiple sectors, including medical, pharmaceutical, and scientific laboratories. These advancements have been particularly evident in developed countries, where the integration of automation technologies has enhanced efficiency, accuracy, and overall quality assurance. In contrast, laboratories in developing countries such as PNG continue to rely predominantly on manual processes, largely due to limitations in financial resources, infrastructure, and technical capacity. Despite these constraints, the technologies identified in the literature, such as artificial intelligence, the Internet of Things, robotics, and Laboratory Information Management Systems, demonstrate strong potential for application within PMTLs, provided that they are appropriately adapted to the local context. PMTLs play a critical role in transportation engineering by ensuring the quality and certification of pavement materials, thereby supporting reliable road design and construction outcomes.

A key finding of this study is the identification of a significant research and operational gap: namely, the absence of an integrated, end-to-end automated system capable of linking test requests, sample handling and registration, personnel allocation, and equipment monitoring within a unified framework. This lack of integration contributes to inefficiencies, limited traceability, and an increased risk of errors in laboratory operations. Furthermore, inadequate laboratory infrastructure continues to compromise safety, quality, and compliance with established standards, presenting an ongoing challenge for PMTLs in resource-constrained environments. The results obtained from the case study further highlight that, despite these challenges, PMTLs in PNG operate under considerable pressure to deliver timely and accurate results in response to the increasing demand. While laboratories strive to maintain reliability in their outputs, the findings reveal that the risks associated with manual processes, particularly in relation to data handling, traceability, and error management, are significant and may undermine the integrity of test results. These findings underscore the urgent need for the development and implementation of a customized automation framework tailored to the specific operational and resource conditions of PMTLs in developing countries. Such a system would address existing inefficiencies, enhance data integrity, and improve overall laboratory performance, thereby supporting the delivery of high-quality and sustainable road infrastructure.

CONCLUSION

This study demonstrates that digital automation technologies have significantly transformed laboratory operations across medical, scientific, and industrial sectors, leading to improved efficiency, reduced reliance on manual labour, and enhanced quality and reliability of results. Despite these advancements, PMTLs remain largely dependent on manual processes, particularly in areas such as sample handling, test scheduling, personnel coordination, and equipment utilisation. The findings of this research highlight the strong potential of adopting automation technologies, including AI, the IoT, robotics, and LIMS, to transform PMTL operations. However, it is evident that a generic approach to automation is insufficient; instead, a customized and context-specific system design is required to effectively address the unique operational challenges and constraints of PMTL environments.

While the benefits of automation are substantial, the study identifies sustainability as a critical barrier to successful implementation. Challenges related to financial constraints, infrastructure limitations, and technical capacity continue to hinder the adoption of automation in developing countries. In particular, the digitalisation of laboratory equipment, data processing systems, and reporting mechanisms requires consistent investment and long-term strategic support. Therefore, the successful implementation of PMTL automation depends not only on the availability of appropriate technologies but also on sustained funding, infrastructure development, and capacity building. Addressing these factors is essential to enable the transition toward integrated, automated laboratory systems that improve operational efficiency, ensure data integrity, and support the delivery of high-quality and sustainable road infrastructure.

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