"Improving Laboratory Operations and Patient Care through Total Laboratory Automation"

Dr. Anjali J. Kelkar, Dr. Vaishali T. Patil

Ruby Hall Clinic, India

DOI: https://dx.doi.org/10.51584/IJRIAS.2026.11010071

Received: 20 January 2026; Accepted: 26 January 2026; Published: 06 February 2026

ABSTRACT

Background

Clinical laboratories are experiencing increasing test volumes, expanding test menus, and sustained pressure to deliver rapid and reliable turnaround times (TAT) amid workforce constraints. Total laboratory automation (TLA) has emerged as a systems-level approach to address these challenges; however, real-world evaluations focusing on workflow transformation and variability reduction remain limited.

Objectives

To evaluate the impact of comprehensive TLA on workflow efficiency, TAT performance, and process stability across core laboratory disciplines.

Methods

A retrospective operational evaluation was performed comparing laboratory performance before and after TLA implementation using LIS data. TAT performance was assessed using the proportion of samples meeting predefined targets across chemistry, immunology, and hematology disciplines. Process stability and variability were evaluated using statistical process control methods. Reductions in manual workflow steps and sample handling touchpoints were quantified. TAT performance for time-critical assays was assessed on the automated track.

Results

Implementation of TLA resulted in 56% reduction in manual workflow steps and a 75% reduction in sample handling touchpoints. Post-automation, the proportion of samples meeting TAT targets improved across all disciplines, accompanied by significant narrowing of performance variability. On the TLA line, 81–86% of chemistry tests were reported within 30 minutes, and up to 89% of high-sensitivity troponin I results were available within 40 minutes with improved process stability.

Conclusions

Comprehensive TLA significantly improved workflow efficiency, TAT performance, and process stability in a high-volume tertiary care laboratory. Beyond reductions in absolute TAT, automation enhanced predictability and operational control, supporting clinical decision-making, quality governance, and readiness for data-driven laboratory practice.

Keywords: Total Laboratory Automation, Laboratory Operations, Turnaround Time, Workflow Efficiency, Process Stability

INTRODUCTION

Clinical laboratories play a pivotal role in modern healthcare, with an estimated 60–70% of clinical decisions influenced by laboratory test results. Over the past several decades, laboratories have experienced steadily increasing test volumes, expanding test menus, heightened expectations for rapid turnaround time (TAT), and persistent workforce constraints. These pressures have driven a progressive transition from manual and semi-

automated workflows toward integrated automation strategies encompassing the entire total testing process [1,2]

Total laboratory automation (TLA) represents the most advanced stage of laboratory automation, integrating pre-analytical, analytical, and post-analytical phases through automated sample handling, analyzer connectivity, middleware-based decision rules, and centralized data management. [3,4] Early automation efforts focused primarily on analytical throughput and consolidation; however, contemporary TLA systems emphasize end-to-end workflow redesign, reduction of manual interventions, standardization, and real-time process control. [5,6]

Multiple studies have demonstrated that implementation of TLA is associated with significant improvements in laboratory efficiency and turnaround time performance. Reductions in overall TAT and narrowing of TAT variability have been consistently reported across core laboratory and tertiary care settings, particularly for chemistry and immunology testing. Importantly, improved routine TAT performance has been shown to reduce dependence on STAT testing, thereby optimizing workflow prioritization and resource utilization. [7,8]

Beyond absolute reductions in TAT, TLA has been shown to improve process stability and predictability. Statistical process control–based analyses demonstrate reduced dispersion, fewer outliers, and sustained performance improvements following automation. [9] Long-term and multicenter evaluations further suggest that these benefits are durable and scalable, extending across consolidated laboratory networks and high-throughput academic centers. [10,11]

In parallel, TLA has emerged as a critical enabler of quality governance. Automation supports standardized pre-analytical processing, enhanced traceability, rule-based auto-verification, and systematic application of quality control and delta check rules, all of which contribute to reduced human error and improved compliance with accreditation standards. [12–14] However, several authors caution that automation does not obviate the need for clinical oversight, and that governance structures remain essential to ensure patient safety and appropriate result interpretation in highly automated environments. [15,16]

Technological advances have further expanded the scope of TLA beyond traditional core laboratory disciplines. Integration of digital morphology, automated urinalysis, microbiology automation, and mass spectrometry workflows has broadened the applicability of automation across diagnostic domains. [17–20] At the same time, enhanced middleware functionality and data integration have positioned TLA as a foundational platform for artificial intelligence (AI)–enabled diagnostics, predictive analytics, and clinical decision support systems [8,21]

Recent literature increasingly conceptualizes TLA as a cyber-physical system within an “Automation 4.0” paradigm, in which continuous data streams enable adaptive optimization rather than static workflow automation. [6,8] In this context, automation supports not only operational efficiency but also diagnostic stewardship, longitudinal data analysis, and future-ready laboratory medicine. [22,23]

Despite its advantages, implementation of TLA remains complex and resource intensive. Economic evaluations indicate that while capital investment is substantial, long-term benefits may include improved cost efficiency, optimized manpower utilization, and reduced waste when automation systems are appropriately scaled and aligned with institutional needs. [24,25] Conversely, several reports emphasize that not all laboratories are ideal candidates for full TLA and that poor alignment between workflow design, vendor capabilities, and governance structures may limit realized benefits. [4,15]

Importantly, much of the published TLA literature originates from high-income settings, with relatively limited data from rapidly expanding tertiary care laboratories in resource-variable environments. Furthermore, many studies focus primarily on mean TAT reduction, with fewer evaluations examining variability, process stability, and discipline-specific workflow transformation using statistical process control methodologies. [2,9] India’s diagnostic laboratories operate within a uniquely high-pressure environment characterized by very high test volumes, wide case-mix variability, workforce constraints, and increasing expectations for rapid and reliable turnaround times. Large tertiary care hospitals and expanding reference laboratory networks must simultaneously address operational efficiency, quality assurance, and accreditation requirements while supporting clinical decision-making for complex patient populations. In this context, TLA has emerged as a strategic solution, enabling integration of pre-analytical, analytical, and post-analytical workflows across

disciplines such as biochemistry, immunology, hematology, and digital morphology. Early Indian experiences have demonstrated the feasibility of implementing comprehensive automation platforms within resource-constrained yet high-throughput settings, including the establishment of structured validation and verification protocols for automated core laboratories. [26,27] Select Indian studies have also reported improvements in analytical performance and turnaround time following automation in specific testing domains, such as HbA1c analysis in tertiary care laboratories. [28] However, systematic evaluations from India remain limited, particularly those examining workflow stability, process predictability, and operational resilience beyond mean turnaround time reductions. Generating context-specific Indian data is therefore essential to inform adoption decisions, guide governance frameworks, and align automation initiatives with patient-centred care delivery in rapidly evolving healthcare systems.

In this context, the present study describes the implementation of a comprehensive total laboratory automation system in a high-volume hospital based laboratory. The study evaluates the impact of TLA on manual workflow steps, sample touchpoints, turnaround time performance, and process variability across chemistry, immunology, and hematology disciplines. By integrating operational metrics with statistical process control–based analyses, this work aims to provide real-world evidence on how TLA can transform laboratory performance while supporting quality governance, scalability, and future readiness.

The aim of this study was to evaluate the impact of comprehensive total laboratory automation on workflow efficiency, turnaround time performance, and process stability in a high-volume hospital based laboratory. Specifically, the study assessed changes in discipline-specific turnaround time target achievement and variability using statistical process control methods, quantified reductions in manual workflow steps and sample handling touchpoints, compared post-automation performance across chemistry, immunology, and hematology disciplines, and examined the ability of automated workflows to achieve clinically relevant short-interval reporting benchmarks. In addition, the study describes the governance-driven procurement, implementation, and monitoring framework supporting sustainable laboratory automation.

METHODS

Study Design and Setting

This retrospective, observational operational evaluation was conducted in a high-volume laboratory part of an 800-bedded specialty hospital between December 2023 and September 2025. The laboratory provides diagnostic services to both inpatient and outpatient populations and supports postgraduate teaching programs. The study evaluated laboratory workflow and turnaround time (TAT) performance before and after implementation of comprehensive total laboratory automation (TLA). Performance data were extracted from the laboratory information system (LIS) for predefined pre-automation and post-automation periods, with the installation and stabilization phase deliberately excluded to ensure assessment of mature system performance. A retrospective before–after design was selected to assess the real-world impact of a complex systems intervention such as TLA. The primary objective was not patient-level causal inference but systematic evaluation of workflow transformation, TAT behavior, and process stability under routine service conditions. Use of routinely captured LIS data enabled analysis across high test volumes and extended observation periods, reflecting sustained operational performance rather than short-term pilot effects.

Total Laboratory Automation Architecture

The TLA system comprised integrated pre-analytical, analytical, and post-analytical components supported by centralized middleware connectivity (Beckman Coulter India Private Limited). The automation track included a DXA5000 Fit system connected to two DXC700AU chemistry analyzers with integrated ISE, one DXI800 immunoassay analyzer with backup, and two DXH900 hematology analyzers integrated with an automated slide maker and stainer (SMS). Pre-analytical automation included automated sample reception, barcode identification, intelligent sample sorting, online centrifugation, and automated routing to connected analyzers. Post-analytical automation comprised automated sample archiving and retrieval. Urine chemistry samples were incorporated into the automated workflow, enabling standardized processing within the TLA ecosystem. Coagulation and clinical pathology testing were not analytically placed on the automation track but were integrated through the middleware platform, allowing centralized rule-based processing, result validation, and workflow visibility despite off-track analysis.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume XI Issue I January 2026

Pre-Analytical Workflow and Sample Handling

All eligible whole blood, serum, and plasma samples underwent automated barcode verification and sorting upon receipt. Online centrifugation was performed under standardized conditions, after which samples were automatically routed to the appropriate analytical platforms. Coagulation samples were similarly sorted and centrifuged through the pre-analytical automation module and held ready for loading onto coagulation analyzers, ensuring uniform pre-analytical handling while preserving discipline-specific analytical workflows. Automated pre-analytical checks facilitated early detection of sample-related issues, reducing manual intervention and improving consistency of sample preparation across disciplines.

Middleware Integration and Rule-Based Processing

A centralized middleware platform (Remisol) served as the operational backbone of the TLA system. Middleware functionality included analyzer interfacing, real-time sample tracking, rule-based auto-validation, reflex and rerun testing rules, and quality control management. Integration of coagulation and clinical pathology workflows through middleware enabled standardized validation logic, centralized monitoring, and harmonized reporting across disciplines, despite differences in analytical platforms.

Turnaround Time Definitions and Performance Metrics

Turnaround time was defined as the interval from sample reception in the laboratory to final result authorization in the LIS. Institutional TAT targets were defined separately for chemistry, immunology, and hematology disciplines based on clinical requirements. Due to limitations in historical LIS data extraction, median and interquartile range values could not be uniformly derived across all study periods. Accordingly, TAT performance was assessed using the proportion of samples meeting predefined targets, a metric that emphasizes reliability and consistency of service delivery. Short-interval TAT benchmarks were additionally evaluated for time-critical assays processed on the TLA line, including chemistry tests and selected immunoassays. Formal hypothesis testing was not emphasized, as the primary objective was operational performance evaluation rather than inferential comparison.

Assessment of Workflow Efficiency

Workflow efficiency was evaluated through structured mapping of the total testing process across pre-analytical, analytical, and post-analytical phases. Manual workflow steps and sample handling touchpoints were enumerated using standardized process documentation and direct observation. Touchpoints were defined as discrete manual actions involving sample movement, decision-making, or physical handling from sample receipt through result validation and sample storage. Counts were performed separately for each discipline and subsequently aggregated to estimate overall reductions attributable to automation. Percentage reductions in manual steps and touchpoints following TLA implementation were calculated.

Statistical Process Control Analysis

Process stability and variability were assessed using statistical process control methods. Individuals–moving range (XmR) charts were generated to evaluate TAT dispersion, identify outliers, and compare process behavior before and after automation. Reductions in TAT variability were estimated based on changes in dispersion and control limits across study periods. Outliers were defined using predefined institutional thresholds. Statistical process control was selected to evaluate system-level performance behavior over time rather than isolated point estimates.

Procedural Governance and Data Integrity

All data were extracted directly from the LIS and middleware platforms using predefined queries to ensure consistency across study periods. Data cleaning procedures included exclusion of the installation and stabilization phase, removal of non-routine test categories, and predefined handling of extreme outliers based on institutional thresholds. No manual manipulation of turnaround time data was performed beyond these predefined criteria.

Governance oversight was embedded throughout the automation lifecycle, including procurement, validation, rule configuration, and ongoing performance monitoring. This approach ensured that observed performance changes reflected system redesign rather than ad hoc operational adjustments, strengthening the internal validity of the evaluation.

Ethical Considerations

The study was conducted as a retrospective analysis of operational laboratory data with no access to patient identifiers. As no interventions were performed and no patient-level clinical outcomes were analyzed, formal ethical committee approval was not required in accordance with institutional policy.

RESULTS

Laboratory Profile and Baseline Workflow Characteristics

The evaluation was conducted in a high-volume hospital based laboratory processing approximately 1,500 samples and 12,000 tests per day across multiple core disciplines. The laboratory supported more than 30,000 inpatient and over 120,000 outpatient encounters annually, with a test menu exceeding 150 assays. Prior to automation, workflows were characterized by high levels of manual intervention, multiple standalone analyzers, and fragmented pre- and post-analytical processes across disciplines.

Table 1. Laboratory Characteristics and Test Volumes Before TLA Implementation

Parameter	Value
Annual inpatient volume	>30,000
Annual outpatient volume	>120,000
Daily samples processed	~1,500
Daily tests performed	~12,000
Number of laboratory disciplines	10
Test menu size	>150 tests
Biochemistry & Immunoassay analyzers	7 analyzers (6 vendors)
Hematology & Coagulation analyzers	4 analyzers (3 vendors)
Laboratory sites	3
Academic role	Post Graduate teaching

Reduction in Manual Workflow Steps and Sample Handling Touchpoints

Implementation of total laboratory automation resulted in a substantial transformation of laboratory workflows. Prior to automation, biochemistry samples required approximately 13 manual touchpoints from sample receipt to analyzer unloading, while hematology and coagulation samples involved up to 24 touchpoints when post-analytical handling was included. Following automation, overall sample handling touchpoints were reduced by approximately 75% across disciplines. Manual workflow steps in the pre- and post-analytical phases decreased by approximately 56%, reflecting a shift toward standardized, automation-driven processes. Automated sample reception, online centrifugation, middleware-based routing, and automated archiving collectively contributed to reduced manual handling and improved workflow consistency.

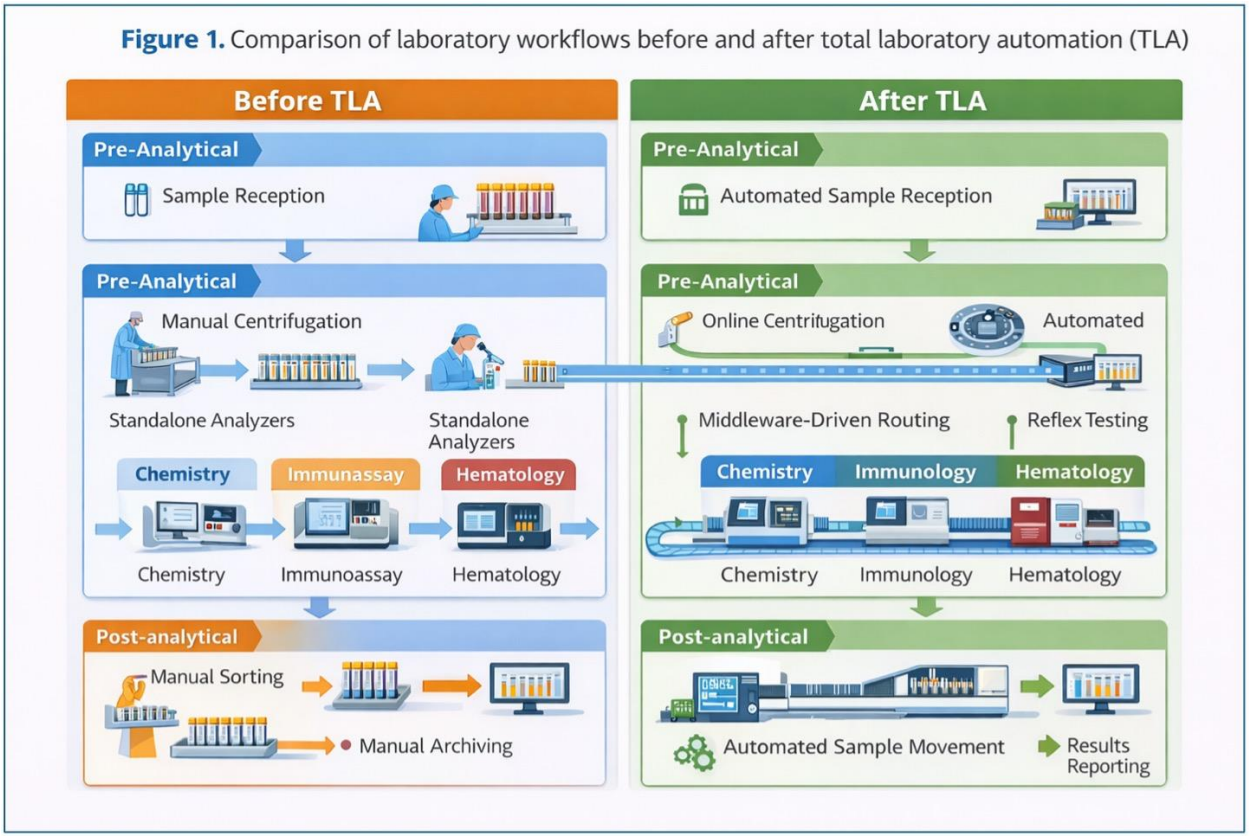
Table 2. Comparison of Manual Touchpoints and Workflow Steps Before and After TLA

Discipline	Pre-TLA touchpoints (n)	Post-TLA touchpoints (n)	Percentage reduction
Biochemistry	13	3–4	70–75%

Hematology	24	6	75%
Coagulation	24	6	75%
Overall laboratory workflow	High manual intervention	Predominantly automated	75%

Table 2 Note: Touchpoints were counted from sample receipt to analyzer unloading for pre-analytical and analytical phases, and from result validation to sample storage for post-analytical processes.

Figure 1. Laboratory workflows before and after automation



Turnaround Time Target Achievement Before and After Automation

Turnaround time (TAT) performance was evaluated using discipline-specific institutional targets. In the pre-automation period, achievement of TAT targets showed wide variability across disciplines and test categories. Following implementation of TLA, the proportion of samples meeting predefined TAT targets improved across chemistry, immunology, and hematology disciplines. Overall laboratory TAT variability decreased by approximately 16% following automation. Discipline-specific reductions in variability were observed, with chemistry demonstrating a 21% reduction, immunology a 36% reduction, and hematology a 28% reduction in TAT variability. These findings indicate improved predictability and consistency of laboratory performance rather than isolated improvements in average reporting times.

Table 3. Turnaround Time Performance Before and After TLA (TAT target: 240 minutes for all disciplines*)*

Discipline	% samples meeting TAT target (Pre-TLA)	% samples meeting TAT target (Post-TLA)	Reduction in TAT variability (%)
Chemistry	63–90%	80–86%	21%
Immunology	49–90%	75–88%	36%
Hematology	Variable	Improved	28%

Overall laboratory	Variable	Improved	16%

Table 3 Note: Turnaround time targets were discipline specific and defined according to institutional benchmarks. Median and interquartile range values were not consistently extractable from legacy laboratory information system data; therefore, turnaround time performance was assessed using proportion of samples meeting predefined targets and variability reduction derived from statistical process control analysis.

Table 4. Short-Interval TAT Achievement on TLA Line - Proportion of tests achieving short-interval turnaround time benchmarks following total laboratory automation.

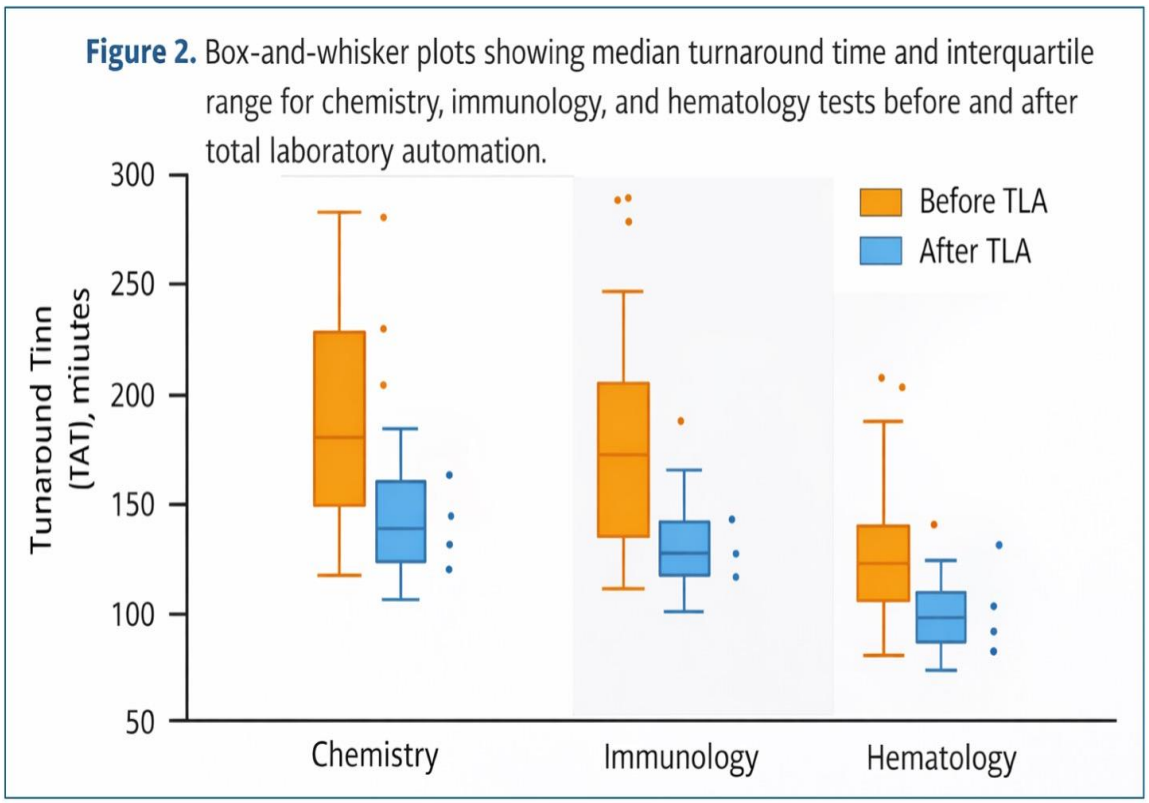
Test category	Time threshold	% tests reported within threshold
Chemistry tests (CC)	≤30 minutes	81–86%
Potassium (K)	≤30 minutes	86–90%
Immunoassays (overall)	≤60 minutes	~78%
High-sensitivity Troponin I	≤40 minutes	Up to 89%

Includes rerun tests completed within 4 hours; outliers defined as <5 or >240 minutes.

Distribution of Turnaround Time and Variability Reduction

Comparative analysis of turnaround time distributions before and after automation demonstrated narrowing of dispersion across all major disciplines. Box-and-whisker plots showed reduced spread and fewer extreme values in the post-automation period for chemistry, immunology, and hematology testing, consistent with improved process stability.

Figure 2. Comparison of TAT and variability before and after automation

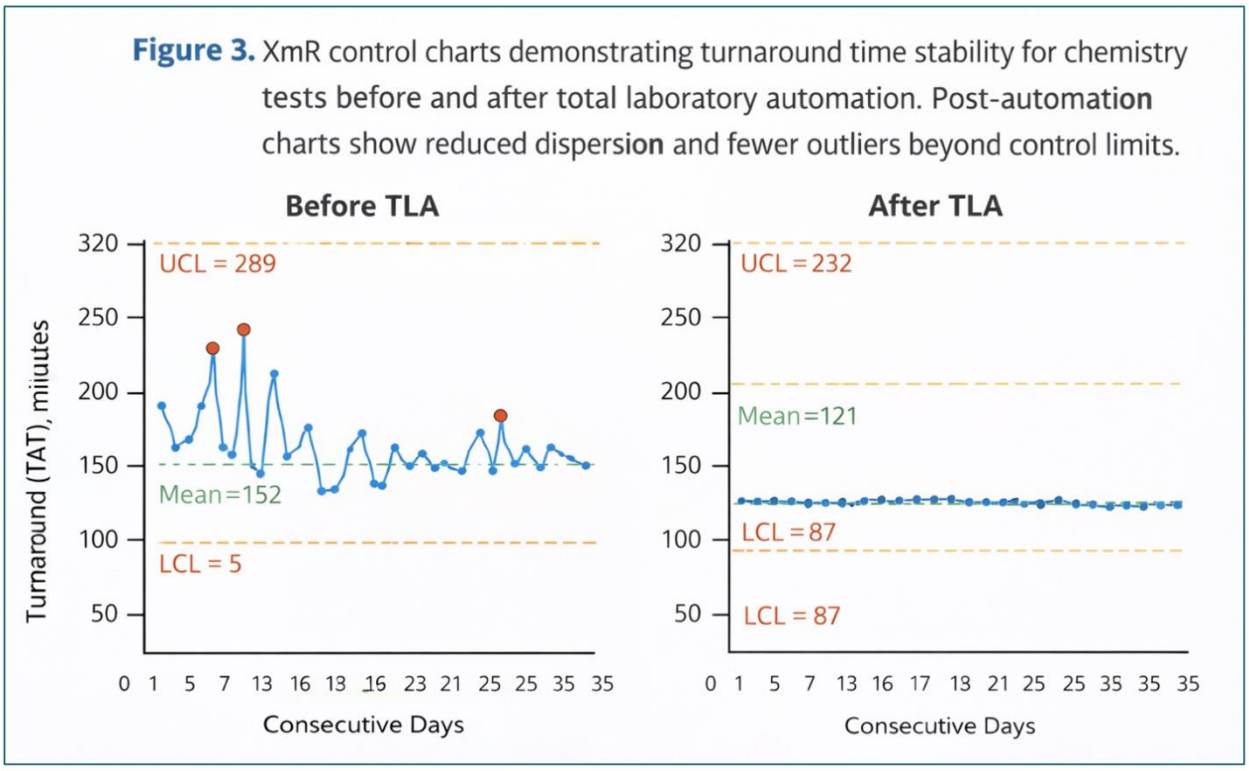


Statistical process control analysis further confirmed stabilization of laboratory workflows following automation. Individuals–moving range (XmR) charts for chemistry turnaround time demonstrated reduced

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume XI Issue I January 2026

dispersion and fewer outliers beyond control limits in the post-automation period compared with pre-automation performance.

Figure 3. TAT Stability



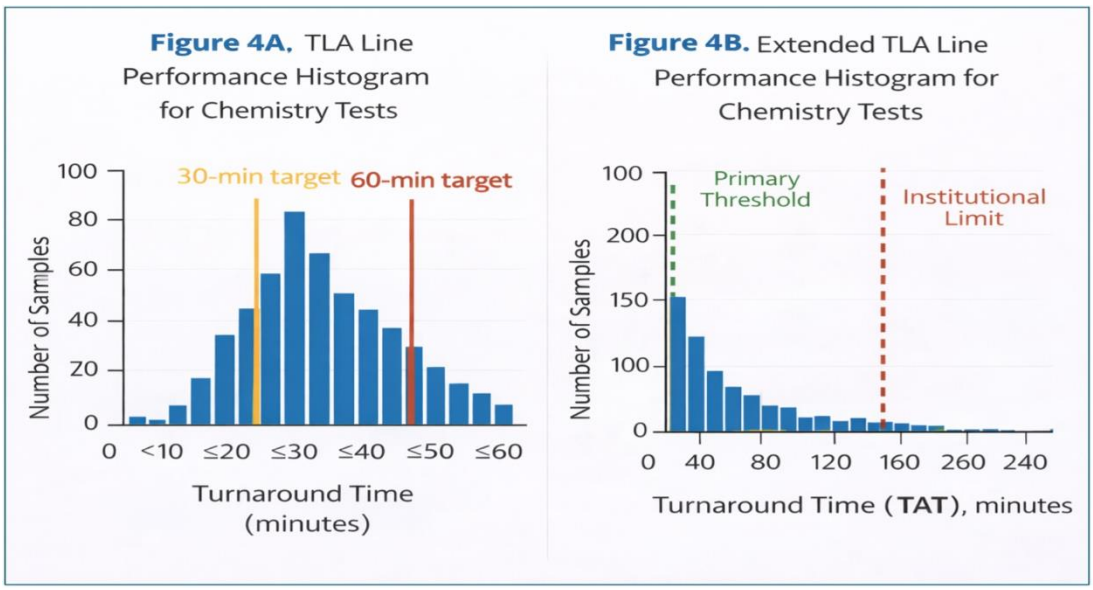
Turnaround Time Performance on the TLA Line

Performance on the total laboratory automation line was assessed using short-interval turnaround time benchmarks for time-sensitive testing. For chemistry assays processed on the automated track, 81–86% of tests were reported within 30 minutes, including rerun samples completed within four hours.

Histogram analysis using clinically defined benchmarks demonstrated a high concentration of results within early reporting intervals, supporting effective routine and urgent test handling.

Extended histogram analysis incorporating institutional operational limits demonstrated a low frequency of delayed results approaching the upper turnaround time threshold, indicating sustained process control across the full reporting range.

Figure 4 (A & B). TLA Line performance: Chemistry tests



ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume XI Issue I January 2026

Immunology Turnaround Time Performance

Immunology assays processed on the TLA line also demonstrated improved turnaround time performance. Approximately 78% of immunoassay results were reported within 60 minutes. High-sensitivity troponin I testing showed particularly strong performance, with up to 89% of results available within 40 minutes, supporting rapid clinical decision-making in acute care settings.

Figure 5. TLA Line performance – Immunology tests

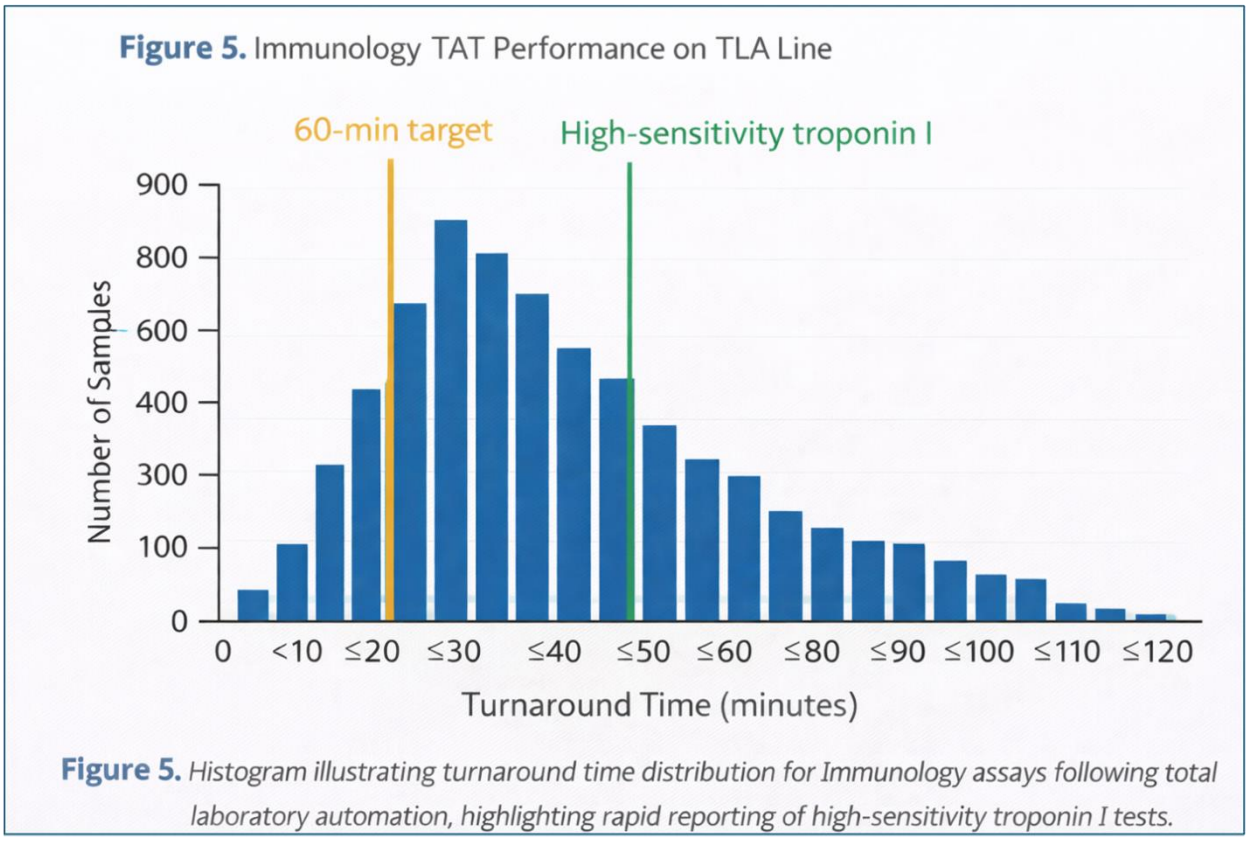


Figure 5. *Histogram illustrating turnaround time distribution for Immunology assays following total laboratory automation, highlighting rapid reporting of high-sensitivity troponin I tests.*

Hematology Workflow Optimization and Resource Utilization

Integration of hematology analyzers with automated slide preparation, staining systems, and digital morphology platforms resulted in improved workflow efficiency. Middleware-driven reflex and rerun rules reduced manual decision-making steps and waiting times for result verification. Adoption of a shared-tube strategy for compatible assays, such as complete blood count and HbA1c testing, resulted in savings of more than 13,000 sample tubes over the evaluation period.

Table 5. Hematology Workflow Optimization and Resource Utilization: Impact of total laboratory automation on hematology workflow efficiency and consumable utilization.

Parameter	Pre-TLA	Post-TLA
Slide preparation	Manual	Automated (SMS integrated with TLA)
Slide staining	Manual	Automated
Morphology review	Conventional microscopy	Digital morphology

Reflex/rerun rules	Manual decision-making	Middleware-driven automated rules
Sample tubes used (CBC + HbA1c)	Separate tubes	Shared-tube strategy
Tubes saved	Not applicable	>13,000 tubes

Summary of Key Performance Outcomes

Collectively, total laboratory automation was associated with marked reductions in manual workflow steps and sample handling touchpoints, improved turnaround time target achievement, and significant narrowing of turnaround time variability across disciplines. Statistical process control analysis demonstrated enhanced process stability, while short-interval performance metrics highlighted the laboratory's ability to deliver rapid results for time-critical testing.

DISCUSSION

We present a practical account of implementing comprehensive total laboratory automation (TLA) in a high-volume, hospital-based laboratory. While TLA has increasingly been adopted as a strategic response to rising laboratory workloads, workforce constraints, and escalating expectations for rapid and reliable turnaround times (TAT), the present findings demonstrate that its principal value lies not simply in accelerating test processing, but in enabling a fundamental redesign of laboratory workflows toward greater consistency, predictability, and operational resilience. This interpretation is particularly relevant in the Indian context, where early reports have focused predominantly on feasibility, validation, and selective analytical gains rather than sustained end-to-end operational transformation [26–28]. By emphasizing workflow stability and variability reduction, the current study advances the understanding of TLA as an organizational intervention rather than a purely technological upgrade.

Prior to automation, laboratory operations were characterized by multiple non–value-adding activities, including excessive manual sample movement, repeated handling, fragmented analyzer layouts, and dependence on individual staff vigilance for managing urgent and add-on requests. These conditions resulted in variable TAT performance and imposed substantial cognitive and physical burden on laboratory personnel. Such inefficiencies are well described in high-throughput laboratories globally and are particularly pronounced in Indian healthcare systems, where diagnostic demand often expands faster than workforce capacity and infrastructure development. Consistent with this, industry and institutional reports from India identify fragmented workflows and workforce strain as primary drivers for adoption of TLA [1,2,27], reinforcing the relevance of the present findings to real-world operational challenges.

Implementation of TLA in this study led to marked improvements in workflow efficiency, turnaround time performance, and process stability across chemistry, immunology, and hematology disciplines. Crucially, these benefits extended beyond reductions in mean or median TAT to include substantial narrowing of TAT variability, reflecting improved predictability and operational control. This distinction is clinically meaningful, as variability reduction has increasingly been recognized as a more informative indicator of laboratory performance than absolute TAT alone [9,15]. Predictable reporting timelines are essential for coordinated clinical decision-making, particularly in emergency, critical care, and oncology settings, where uncertainty in result availability can disrupt care pathways even when average performance appears acceptable.

The magnitude and consistency of TAT improvement observed are broadly concordant with prior reports from large core laboratories and tertiary care institutions, where reductions in overall TAT following TLA implementation—especially for routine chemistry and immunoassay testing—have been consistently demonstrated [24,29,30]. Similar benefits reported from consolidated laboratory networks and academic medical centers further support the scalability of TLA across diverse operational contexts [10,11]. Although Indian data remain limited, available studies have documented improvements in analytical performance and TAT following automation in selected testing domains [28]. The present work extends this emerging evidence

by demonstrating sustained performance stability across multiple disciplines and care settings, rather than isolated improvements in specific assays. A critical insight from this experience is that the most meaningful improvement was the reduction in process variability rather than isolated gains in speed. While many earlier studies emphasized average TAT reduction, fewer systematically examined dispersion and process behavior. In routine clinical practice, variability in reporting times can be as disruptive as prolonged TAT, undermining clinician confidence and workflow planning. The observed narrowing of interquartile ranges and improvement in statistical process control metrics are consistent with findings reported by Mayne et al. (2020), who demonstrated enhanced Six Sigma performance following automation [9]. Together, these observations reinforce the role of TLA as a systems-level intervention designed to stabilize laboratory processes rather than merely accelerate individual test pathways.

Improved routine TAT performance also has important downstream implications for STAT testing behavior. Prior studies have shown that reliable routine TAT reduces the perceived need for STAT ordering, thereby minimizing workflow disruption and inefficient prioritization [7,8]. In the present study, the consistent achievement of short-interval reporting benchmarks—particularly for chemistry and immunoassays—supports a transition from reactive prioritization to proactive workflow management based on predictable system performance. Such shifts have implications not only for efficiency but also for staff workload distribution and patient flow management.

The pre-analytical phase, widely recognized as the most error-prone component of the total testing process [5], benefited substantially from automation. Automated sample reception, online centrifugation, and intelligent routing reduced manual handling and operator-dependent variability, directly addressing key sources of pre-analytical error. Standardization of centrifugation parameters and early detection of sample-related issues enhanced confidence in reported results, consistent with prior observations that automation improves pre-analytical quality while mitigating human error [14,31]. Structured validation and verification protocols reported from Indian core laboratories further support the feasibility and relevance of such pre-analytical standardization in high-volume settings [26]. Importantly, the benefits observed were not attributable solely to instrument automation, but to comprehensive workflow redesign. Prior to TLA, standalone analyzers operating in silos necessitated repeated manual sample movement and ad hoc decision-making. Following implementation, integration of analyzers through a unified automation track and middleware platform reduced sample touchpoints by approximately 75%. This systems-level transformation is consistent with earlier observations by Sarkozi et al. (2003) and Seaberg et al. (2000), who emphasized that sustainable operational gains arise from reengineering the total testing process rather than incremental automation of isolated steps [3,10]. Hematology workflows, traditionally among the most labor-intensive areas of the laboratory, showed particularly notable gains. Integration of hematology analyzers with automated slide makers, digital morphology systems, and middleware-driven reflex rules reduced waiting times and decision-making delays. These findings align with multicentric evaluations demonstrating acceptable performance and reduced variability of digital morphology compared with conventional microscopy [19]. The adoption of shared-tube strategies further resulted in meaningful reductions in consumable usage, supporting both economic efficiency and sustainability—considerations of particular importance in resource-conscious Indian laboratory environments.

Despite the operational advantages of automation, quality governance and professional oversight remain essential. Prior authors have cautioned that automation does not eliminate the need for expert judgment but instead necessitates more structured oversight frameworks [12,15]. In the present study, middleware-based auto-verification and quality control rules standardized routine decision-making while preserving escalation pathways for complex or atypical cases. This balanced approach aligns with recommendations that automation should augment, rather than replace, laboratory expertise [16]. TLA also has important implications for accreditation and regulatory compliance. Automated traceability, standardized workflows, and centralized data capture enhance documentation, audit readiness, and continuous quality improvement. Previous studies have highlighted the role of automation in strengthening compliance with accreditation standards when implemented within a structured quality framework [13,14]. Indian laboratories implementing TLA have similarly emphasized accreditation alignment and governance as critical enablers of sustained automation benefits [27]. Emerging literature increasingly conceptualizes TLA as a cyber-physical foundation for artificial intelligence–enabled diagnostics and predictive analytics [6,8]. Stable, low-variability workflows are a prerequisite for meaningful machine learning applications, as unstable processes risk amplifying noise rather

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume XI Issue I January 2026

than generating actionable insight. By establishing consistent pre-analytical and analytical processes, TLA creates the conditions necessary for reliable AI deployment and diagnostic stewardship initiatives [21,22].

Although formal cost-effectiveness analysis was beyond the scope of this study, observed reductions in manual steps, consumable usage, and workflow inefficiencies are consistent with prior economic evaluations demonstrating improved cost efficiency following TLA adoption [24,25]. Importantly, long-term sustainability depends on appropriate scaling, vendor selection, and governance structures rather than technology alone [2,4]. Recent evidence further supports the interpretation that automation benefits extend beyond core analytical workflows, with demonstrated reductions in urine culture turnaround times in consolidated laboratories [32], reinforcement of automation as a driver of value-based laboratory medicine [33], and early evaluations showing improved performance through automation of intra-laboratory logistics [34]. Collectively, these findings reinforce that the gains observed in the present study reflect end-to-end transformation of the total testing process rather than isolated efficiency improvements.

Implementation of TLA is inherently complex and resource intensive, and not all laboratories are suitable candidates; benefits may be attenuated in low-volume or highly heterogeneous environments [15]. While the present experience reflects a high-volume hospital-based laboratory, the structured approach to vendor selection, phased implementation, and continuous performance monitoring offers transferable lessons for comparable institutions, including those operating in resource-variable settings. Indian diagnostic laboratories face uniquely high volumes, wide case-mix variability, and escalating expectations for rapid turnaround times, and the present evaluation provides context-specific evidence that Lean-aligned automation improves predictability, scalability, and governance in such environments.

Overall, this study contributes to the existing TLA literature by integrating operational metrics with statistical process control analysis and emphasizing variability reduction and process stability as core outcomes. By moving beyond mean TAT reduction, it addresses an important gap highlighted previously in the literature [2,15], while adding context-specific evidence from a large Indian laboratory to the evolving global discourse on total laboratory automation.

CONCLUSION

Implementation of comprehensive total laboratory automation (TLA) in a high-volume hospital-based laboratory was associated with substantial and sustained improvements in workflow efficiency, turnaround time performance, and, critically, process stability across chemistry, immunology, and hematology disciplines. Reductions in manual workflow steps and sample handling touchpoints translated into more predictable reporting timelines, improved operational control, and enhanced capacity to support time-critical clinical decision-making. These findings reinforce the role of TLA as a systems-level enabler of value-based laboratory medicine, extending benefits beyond speed to include standardization, optimized workforce utilization, and strengthened quality governance. The observed improvements have clear operational relevance for laboratories managing high and heterogeneous workloads. Improved predictability of routine turnaround times reduces reliance on STAT testing, supports rational prioritization, and enhances coordination with clinical care pathways. Integration of pre-analytical, analytical, and post-analytical processes also provides a stable foundation for downstream innovations, including digital morphology, automated microbiology workflows, and data-driven decision support. When aligned with structured governance and workflow redesign, TLA represents an organizational transformation rather than a standalone technological upgrade.

Limitations

This evaluation reflects the experience of a single high-volume tertiary care laboratory and may not be directly generalizable to smaller laboratories, low-throughput environments, or institutions with substantially different case-mix. The retrospective, operational design relied on routinely captured laboratory information system data, limiting uniform extraction of full turnaround time distributions and precluding direct assessment of patient-level clinical outcomes. Formal health-economic analysis was beyond the scope of this study, and the impact of automation on diagnostic error rates, near-miss events, and clinician satisfaction was not directly measured.

Future Directions and Perspective

Future research should prioritize multicenter and longitudinal evaluations that integrate operational metrics with patient-centred outcomes, workforce indicators, and formal cost-effectiveness analyses to better define the clinical and economic value of total laboratory automation across diverse healthcare settings. Comparative studies examining partial versus comprehensive automation, discipline-specific automation strategies, and the incremental impact of automated logistics and sample transport systems would further inform optimal implementation models.

Stable and low-variability workflows established through TLA should be leveraged to support advanced analytics, artificial intelligence–enabled decision support, and diagnostic stewardship initiatives. In this context, TLA can be viewed not only as an efficiency tool but as a foundational infrastructure for future-ready laboratory medicine, enabling scalable, data-driven, and patient-centred diagnostic services in high-demand healthcare environments.

REFERENCES

1. Hawker CD: Laboratory automation: total and subtotal. Clin Lab Med. 2007, 27:749–70, vi. 10.1016/j.cll.2007.07.010
2. Genzen JR, Burnham C-AD, Felder RA, Hawker CD, Lippi G, Peck Palmer OM: Challenges and Opportunities in Implementing Total Laboratory Automation. Clin Chem. 2018, 64:259–64. 10.1373/clinchem.2017.274068
3. Seaberg RS, Stallone RO, Statland BE: The role of total laboratory automation in a consolidated laboratory network. Clin Chem. 2000, 46:751–6.
4. Thomson RB, McElvania E: Total Laboratory Automation. Clinics in Laboratory Medicine. 2019, 39:371–89. 10.1016/j.cll.2019.05.002
5. Lippi G, Da Rin G: Advantages and limitations of total laboratory automation: a personal overview. Clin Chem Lab Med. 2019, 57:802–11. 10.1515/cclm-2018-1323
6. Nam Y, Park HD: Revolutionizing Laboratory Practices: Pioneering Trends in Total Laboratory Automation. Ann Lab Med. 2025, 45:472–83.
7. Dolci A, Giavarina D, Pasqualetti S, Szőke D, Panteghini M: Total laboratory automation: Do stat tests still matter? Clinical Biochemistry. 2017, 50:605–11. 10.1016/j.clinbiochem.2017.04.002
8. Ialongo C, Porzio O, Giambini I, Bernardini S: Total Automation for the Core Laboratory: Improving the Turnaround Time Helps to Reduce the Volume of Ordered STAT Tests. J Lab Autom. 2016, 21:451–8. 10.1177/2211068215581488
9. Mayne ALH, Mayne ES, Louw S: Proposed application of six sigma metrics using a gamma distribution to monitor turnaround time for a high-volume coagulation test before and after introduction of a total laboratory automation platform in an academic laboratory in South Africa. Int J Lab Hematol. 2020, 42:e124–7. 10.1111/ijlh.13163
10. Sarkozi L, Simson E, Ramanathan L: The effects of total laboratory automation on the management of a clinical chemistry laboratory. Retrospective analysis of 36 years. Clin Chim Acta. 2003, 329:89–94. 10.1016/s0009-8981(03)00020-2
11. Tseng C-W, Li Y-C, Lee H-S, Tseng Y-M: Laboratory testing consolidation and total laboratory automation improves service efficiency and effectiveness: a study of a medical center in Taiwan. Lab Med. 2024, 55:677–85. 10.1093/labmed/lmae044
12. Pasqualetti S, Birindelli S, Aloisio E, Dolci A, Panteghini M: Clinical Governance Remains a Priority in Total Laboratory Automation Era. The Journal of Applied Laboratory Medicine. 2019, 4:130–2. 10.1373/jalm.2018.028035
13. Markus C, Tan RZ, Loh TP: Evidence-based approach to setting delta check rules. Crit Rev Clin Lab Sci. 2021, 58:49–59. 10.1080/10408363.2020.1800585
14. Brown AS, Badrick T: The next wave of innovation in laboratory automation: systems for auto-verification, quality control and specimen quality assurance. Clin Chem Lab Med. 2023, 61:37–43. 10.1515/cclm-2022-0409
15. Plebani M: Total laboratory automation: fit for its intended purposes? Clin Chem Lab Med. 2026, 64:22–6. 10.1515/cclm-2025-0855
16. El-Khoury JM: Breaking the Chain: Navigating the Pitfalls of Total Laboratory Automation. J Appl Lab Med. 2024, 9:1095–6. 10.1093/jalm/jfae061

17. Bartosova K, Kubicek Z, Franekova J, Louzensky G, Lavrikova P, Jabor A: Analysis of Four Automated Urinalysis Systems Compared to Reference Methods. Clin Lab. 2016, 62:2115–23. 10.7754/Clin.Lab.2016.160316
18. Burckhardt I: Laboratory Automation in Clinical Microbiology. Bioengineering. 2018, 5:102. 10.3390/bioengineering5040102
19. Da Rin G, Seghezzi M, Padoan A, et al.: Multicentric evaluation of the variability of digital morphology performances also respect to the reference methods by optical microscopy. Int J Lab Hematol. 2022, 44:1040–9. 10.1111/ijlh.13943
20. Salvagno GL, Danese E, Lippi G: Mass spectrometry and total laboratory automation: opportunities and drawbacks. Clin Chem Lab Med. 2020, 58:994–1001. 10.1515/cclm-2019-0723
21. Çubukçu HC, Topcu Dİ, Yenice S: Machine learning-based clinical decision support using laboratory data. Clin Chem Lab Med. 2024, 62:793–823. 10.1515/cclm-2023-1037
22. Cobbaert C, Albersen A, Zwiers I, Schippers P, Gillis J: Designing a diagnostic Total Testing Process as a base for supporting diagnostic stewardship. Clin Chem Lab Med. 2020, cclm-2020–1251. 10.1515/cclm-2020-1251
23. Poland DCW, Cobbaert CM: Blood self-sampling devices: innovation, interpretation and implementation in total lab automation. Clinical Chemistry and Laboratory Medicine (CCLM). 2025, 63:3–13. 10.1515/cclm-2024-0508
24. Ellison TL, Alharbi M, Alkaf M, et al.: Implementation of total laboratory automation at a tertiary care hospital in Saudi Arabia: effect on turnaround time and cost efficiency. Ann Saudi Med. 2018, 38:352–7. 10.5144/0256-4947.2018.352
25. Kim K, Lee S-G, Kim TH, Lee SG: Economic Evaluation of Total Laboratory Automation in the Clinical Laboratory of a Tertiary Care Hospital. Ann Lab Med. 2022, 42:89–95. 10.3343/alm.2022.42.1.89
26. Das B, Bhat L, Patil R, Tawde V, Kamath S, Pal P: Total lab Automation Validation/Verification Protocol: First Step of Process Excellence Journey in Smart Core Lab in Kokilaben Dhirubhai Ambani Hospital & Medical Research Institute, Mumbai, India. Clinical Chemistry. 2023, 69:hvad097.375. 10.1093/clinchem/hvad097.375
27. Siemens Healthineers: Case Study: How data and automation revolutionized a reference laboratory network in India. 2025.
28. Abstracts of The 52nd Annual Conference of Research Society for the Study of Diabetes in India. Int J Diabetes Dev Ctries. 2024, 44:83–172. 10.1007/s13410-024-01421-6
29. Lou AH, Elnenaei MO, Sadek I, Thompson S, Crocker BD, Nassar B: Evaluation of the impact of a total automation system in a large core laboratory on turnaround time. Clin Biochem. 2016, 49:1254–8. 10.1016/j.clinbiochem.2016.08.018
30. Yu H-YE, Lanzoni H, Steffen T, Derr W, Cannon K, Contreras J, Olson JE: Improving Laboratory Processes with Total Laboratory Automation. Lab Med. 2019, 50:96–102. 10.1093/labmed/lmy031
31. Zhang BY, Wang G, Wang X, Wu BS, Liu D, Zhang QQ, Zheng L, Li BR, Zhang XF, Wu W: Development and assessment of a novel multimedia-based educational software for teaching peripheral blood smear morphology. BMC Med Educ. 2025, 25:397.
32. Daldaban-Dinçer Ş, Aksaray S: The Effect of Total Laboratory Automation on Urine Culture Result Times in a Consolidated Laboratory. Clin Lab. 2023, 69:. 10.7754/Clin.Lab.2022.220736
33. Gruson D, Zima T, Plebani M: Automation in value-based laboratory medicine: driving precision, capacity, and better outcomes. Clin Chem Lab Med. Published Online First: 15 January 2026. 10.1515/cclm-2026-0023
34. Gervasoni J, Pedrazzini D, Cicchinelli M, et al.: Impact of an autonomous delivery robot on sample turnaround time in a clinical laboratory: an early evaluation of first implementation. Clin Chem Lab Med. Published Online First: 10 December 2025. 10.1515/cclm-2025-1336