

Review

Laboratory Automation and Robotics in Indonesia: Challenges, Workforce Transformation, and a Roadmap for Equitable Implementation

Allan Johannes Andaria ^{1,*}, Atna Permana ², Steldy Runtuwene Lantaka ³, Hizkia Svenly Isworo ⁴, and Julystia Pratiwi Egidia Mole ⁵

¹ Department of Medical Laboratory Technology, Health Polytechnic of the Ministry of Health Manado, Manado 95128, North Sulawesi, Indonesia

² Department of Medical Laboratory Technology, University of Mohammad Husni Thamrin, East Jakarta 13550, Special Capital Region of Jakarta, Indonesia

³ Department of Clinical Pathology, Prof. Dr. R. D. Kandou Central General Hospital, Manado 95115, North Sulawesi, Indonesia

⁴ South Bolaang Mongondow Regional General Hospital, South Bolaang Mongondow 95774, North Sulawesi, Indonesia

⁵ Community Health Center of Ranomuut, Manado 95129, North Sulawesi, Indonesia

* Correspondence: allan.andaria@gmail.com

Abstract

The rapid advancement of laboratory automation, robotics, and digital technologies has significantly transformed laboratory medicine worldwide, improving efficiency, diagnostic accuracy, and quality management. However, the adoption of these technologies in developing countries such as Indonesia remains uneven and is influenced by infrastructural, financial, regulatory, and workforce-related challenges. This structured narrative review aimed to critically examine the current landscape of laboratory automation and robotics in Indonesia, with particular emphasis on implementation challenges, workforce transformation among medical laboratory scientists (*Ahli Teknologi Laboratorium Medik*, ATLM), and pathways toward equitable integration. Studies published between 2015 and 2025 were identified through PubMed, Scopus, and Google Scholar, complemented by Indonesian regulatory documents, professional guidelines, and relevant grey literature. The review was informed by PRISMA principles and synthesized narratively to explore technological developments, operational impacts, policy contexts, and implementation barriers relevant to Indonesian laboratory systems. The findings indicate that automation and robotics offer substantial benefits, including improved turnaround time, enhanced quality assurance, reduced laboratory errors, and greater operational efficiency. Nevertheless, significant barriers persist, particularly disparities in digital infrastructure, financial constraints, limited workforce readiness, and the absence of comprehensive implementation frameworks. The review further highlights that automation is reshaping rather than replacing the role of ATLM, shifting professional responsibilities toward digital competency, automation oversight, data interpretation, and quality management. Achieving sustainable laboratory automation in Indonesia therefore requires an equity-centered and systems-oriented approach involving regulatory strengthening, workforce development, infrastructure investment, and multi-stakeholder collaboration. With strategic planning and policy alignment, laboratory automation and robotics hold considerable potential to modernize laboratory services and support Indonesia's broader healthcare transformation agenda.



Academic Editor: Gassan Hodaifa

Received: 26 May 2026

Revised: 29 June 2026

Accepted: 3 July 2026

Published: 5 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons](#)

[Attribution \(CC BY\)](#) license.

Keywords: clinical laboratory; digital health; laboratory management; medical laboratory scientists; health technology implementation

1. Introduction

Recent advances in automation and robotics have profoundly transformed medical laboratory technology worldwide. Automated systems now possess considerable capabilities in managing a spectrum of processes ranging from sample preparation to analytical result interpretation, substantially reducing the likelihood of human error while improving overall laboratory efficiency. These developments have reshaped laboratories from conventional diagnostic units into increasingly integrated and technology-driven environments capable of supporting faster, safer, and more standardized services. However, in developing countries such as Indonesia, where healthcare infrastructure exhibits considerable variability between urban and rural regions, the adoption of advanced laboratory technologies presents not only significant opportunities but also complex challenges that demand careful consideration.

The transition toward automation in laboratory medicine extends beyond technological adoption alone. It involves organizational readiness, workforce adaptation, infrastructure capacity, financial sustainability, and regulatory oversight. While highly automated laboratories are increasingly common in technologically advanced settings, implementation in lower- and middle-income countries often occurs within more heterogeneous health systems, where disparities in infrastructure and human resources may influence both feasibility and long-term sustainability. Consequently, understanding automation within local healthcare contexts becomes essential to ensuring that technological progress contributes meaningfully to laboratory quality and equitable healthcare delivery.

Globally, trends in laboratory automation have increasingly been defined by remarkable progress in robotics and artificial intelligence (AI), including machine learning-based analytical systems, all of which contribute to enhanced efficiency, accuracy, and safety within laboratory settings. Within this review, robotics is discussed as a component of broader laboratory automation systems, while AI refers to computational technologies supporting diagnostic interpretation, workflow optimization, and data-driven decision-making in laboratory medicine. Beyond routine clinical diagnostics, these advanced technologies are becoming deeply integrated into emerging scientific disciplines such as synthetic biology and precision medicine, fostering significant innovation and accelerating the pace of scientific discovery. This convergence signals a paradigm shift in the role of laboratories—from purely analytical functions to active participation in research, development, and personalized healthcare solutions. Nevertheless, while these innovations hold considerable promise, they also introduce substantial challenges, particularly related to the complexity of adopting advanced automation systems and ensuring sustainable implementation in diverse healthcare environments, especially in resource-limited settings like those found in Indonesia [1].

Moreover, the rapid evolution of digital technologies has significantly reshaped public health strategies across Southeast Asia, particularly in response to global health crises and the growing demand for accessible healthcare services. Digital interventions, including telemedicine, mobile health (mHealth) applications, and AI-driven tools, demonstrate immense potential to optimize healthcare delivery and streamline laboratory workflows. However, despite these promising technological advances, substantial gaps remain in the effective implementation and systematic evaluation of digital health solutions across different countries and healthcare contexts in the region. Recent reviews underscore

the critical importance of evidence-based assessments to guide the integration of digital innovations into public health infrastructures, thereby preventing the exacerbation of existing health disparities and ensuring that new technologies truly enhance accessibility, quality, and equity within healthcare systems [2].

At the same time, while digital health technologies are increasingly hailed as transformative assets within healthcare systems, the current body of robust evidence validating their effectiveness across diverse settings remains limited. Strengthening this evidence base through systematic evaluations is therefore essential to ensure that digital health innovations translate into tangible improvements in patient outcomes and can be integrated effectively into various health systems without generating unintended negative consequences [3].

Despite the growing global literature on laboratory automation and digital health transformation, relatively limited attention has been directed toward examining these developments through the specific lens of Indonesia's laboratory ecosystem. Existing discussions often emphasize technological capabilities and efficiency gains while providing less critical examination of contextual issues such as regulatory readiness, infrastructural inequalities, workforce transformation, and equitable implementation. As a result, there remains a need for reviews that move beyond technological description and consider how automation may be integrated sustainably within Indonesia's diverse healthcare environment.

Against this backdrop, this narrative review critically examines the current landscape of laboratory automation and robotics in Indonesia, focusing on technological trends, barriers to implementation, workforce transformation among medical laboratory scientists or *Ahli Teknologi Laboratorium Medik* (ATLM), and the broader policy and organizational implications of automation. By synthesizing international developments alongside Indonesia-specific challenges and opportunities, this review aims to propose a practical roadmap for equitable and sustainable implementation. Understanding these dynamics is critical to ensuring that technological progress translates into genuine improvements in healthcare delivery, laboratory quality, and long-term health system resilience.

2. Methods

This study was conducted as a structured narrative review examining the current state, implementation challenges, workforce implications, and future directions of laboratory automation and robotics in Indonesia, particularly within clinical laboratory services and healthcare settings. The review adopted a narrative synthesis approach while being informed by selected Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) principles to improve transparency in literature identification and screening processes without performing a full systematic review or meta-analysis [4,5].

Literature searches were conducted between January and March 2025 using PubMed, Scopus, and Google Scholar databases. Publications published between 2015 and 2025 in English and Indonesian were considered eligible. Search terms included combinations of "laboratory automation," "robotics," "clinical laboratory," "digital laboratory," "digital health," "artificial intelligence," "Indonesia," "medical laboratory scientists," and "*Ahli Teknologi Laboratorium Medik* (ATLM)," with Boolean operators (AND/OR) applied according to database requirements. Additional sources included Indonesian regulatory documents, national competency standards, professional association guidelines, and relevant grey literature to capture contextual policy and implementation perspectives not consistently represented within indexed databases.

Eligible sources included peer-reviewed articles, review papers, policy documents, competency standards, and reports discussing laboratory automation, robotics, workforce

competencies, healthcare digitalization, laboratory management, and implementation challenges within healthcare laboratory settings. Publications focusing exclusively on non-health industrial automation, unrelated engineering applications, duplicate publications, conference abstracts without accessible full text, and literature lacking relevance to healthcare laboratory practice were excluded.

The initial search identified 96 records, including 24 from PubMed, 31 from Scopus, and 41 from Google Scholar before duplicate removal. After duplicate removal and preliminary relevance screening, 54 publications underwent title and abstract assessment, followed by full-text evaluation of 36 articles and documents. A final total of 28 references were included in the narrative synthesis. The characteristics of the included references, including publication type, geographic focus, and publication period, are summarized in Table 1. Literature screening and eligibility assessment were conducted independently by two authors, with disagreements resolved through discussion and consensus. The literature identification and screening process is summarized in Figure 1.

Table 1. Characteristics of Included References in the Review.

Category	Number	Description
International journal articles	19	Peer-reviewed publications on laboratory automation, AI, robotics, and workforce adaptation
Indonesian regulations and policy documents	5	National regulations, competency standards, and health transformation policies
Grey literature and institutional reports	4	WHO, UNDP, and professional guidance documents
Publication years 2015–2020	8	Early adoption and conceptual literature
Publication years 2021–2025	20	Recent technological and policy developments
Asia-focused literature	11	Singapore, Korea, Southeast Asia, and Indonesia-related studies
Indonesia-specific references	8	National regulations, digital health, and workforce readiness

Extracted information was synthesized thematically to identify recurring patterns related to technological developments, operational efficiency, workforce transformation, regulatory and ethical considerations, implementation barriers, and pathways toward equitable integration. Rather than quantitative evidence aggregation, this review employed narrative synthesis and critical interpretation to contextualize global developments within Indonesia’s healthcare and laboratory ecosystem, consistent with established approaches for structured narrative reviews [4,5].

To complement the literature findings, the review also incorporated the authors’ professional perspectives derived from experiences across private hospitals, private clinical laboratories, and community health centers (PUSKESMAS). These observations were included solely as contextual insights to illustrate practical implementation realities and workforce implications within Indonesian healthcare settings and were not treated as primary evidence.

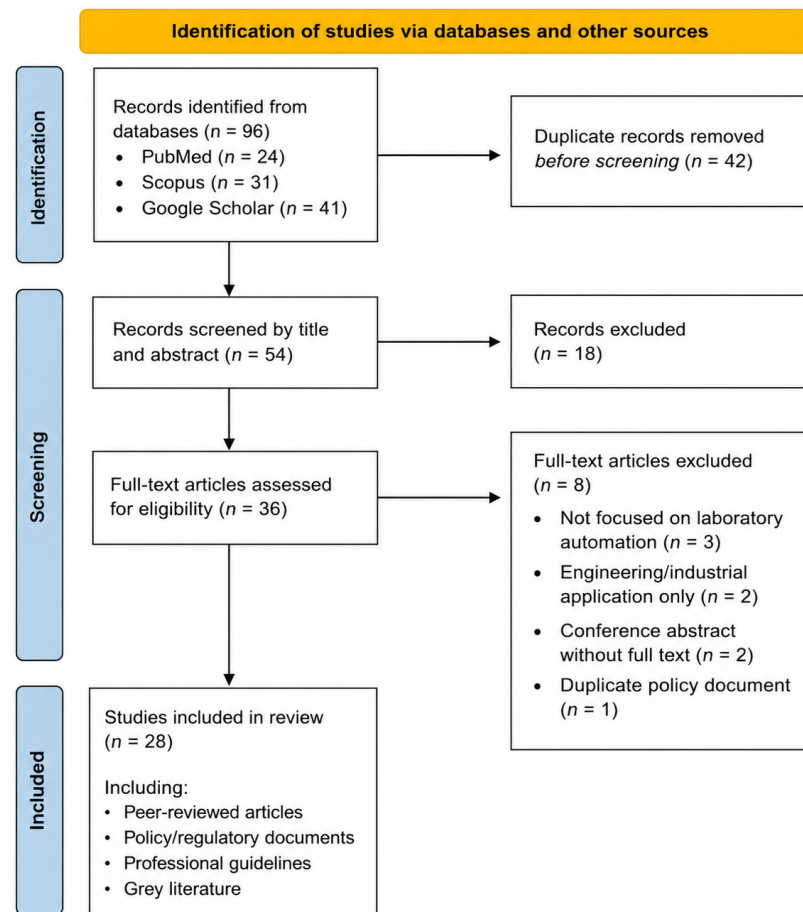


Figure 1. PRISMA-Informed Literature Identification and Screening Process for the Structured Narrative Review.

3. Discussion

3.1. Global Trends in Laboratory Automation and Robotics

Laboratory automation and robotics have become defining features of contemporary laboratory medicine, fundamentally transforming diagnostic workflows and reshaping the operational landscape of healthcare laboratories. Automation now extends across pre-analytical, analytical, and post-analytical phases, enabling laboratories to improve consistency, minimize human error, and accommodate increasing testing demands with greater efficiency and standardization [6]. These technological developments have shifted laboratory operations from labor-intensive procedures toward increasingly integrated systems capable of delivering faster and more reliable diagnostic services.

A major driver of this transformation has been the emergence of sophisticated automated technologies, including robotic sample-handling systems, automated slide preparation devices, and artificial intelligence (AI)-supported diagnostic tools. Contemporary automation platforms are designed not merely to mechanize isolated tasks but to integrate multiple laboratory functions into coordinated workflows. Clinical laboratories implementing advanced automation have reported substantial operational improvements, including enhanced workflow coordination, reduced manual intervention, and more efficient utilization of laboratory space and personnel [7]. Experiences from tertiary healthcare institutions further demonstrate that automation contributes to shorter turnaround times and reduced manual workload, particularly in high-throughput laboratory environments where efficiency and standardization are essential [8].

Beyond conventional automation, laboratory medicine is increasingly influenced by broader technological developments such as AI, machine learning, digital pathology, and data-driven diagnostics. These innovations support improved diagnostic precision and facilitate the development of personalized medicine by enabling faster interpretation of laboratory data and deeper insights into disease processes [9]. The convergence of automation and digital technologies therefore represents more than an operational improvement; it reflects a broader transformation in the strategic role of laboratories, positioning them as active contributors to research, innovation, and precision healthcare.

Among the most significant developments is the emergence of Total Laboratory Automation (TLA), which integrates pre-analytical, analytical, and post-analytical activities into unified and largely autonomous systems. TLA offers several operational advantages, including improved specimen traceability, more efficient resource allocation, and reduced turnaround times through seamless workflow integration [10]. Experiences from automated clinical laboratories indicate that these systems can substantially improve productivity and reduce process variability, particularly when automation is supported by effective laboratory information systems and workflow redesign [7,10].

Despite these advances, the expansion of automation and robotics remains accompanied by important operational and strategic challenges. Sophisticated automated platforms require substantial investment, complex infrastructure, and sustained technical support, factors that may limit implementation in settings with constrained resources [9,10]. Furthermore, the integration of automation within existing laboratory ecosystems often requires significant adaptation of workflows, information systems, and human resource structures to ensure interoperability and sustainable use.

These developments illustrate that laboratory automation is evolving beyond isolated technological innovation toward integrated laboratory ecosystems combining robotics, AI, and digital infrastructure. While these technologies offer unprecedented opportunities to enhance laboratory performance, their successful implementation depends not only on technological capability but also on organizational readiness, workforce adaptation, and contextual suitability. Understanding both the transformative potential and operational limitations of these global trends provides an essential foundation for examining their relevance within Indonesia's laboratory environment.

3.2. Operational and Clinical Benefits of Laboratory Automation

The expansion of laboratory automation has generated substantial operational, clinical, and economic benefits, positioning automation not merely as a technological enhancement but as a strategic component of modern laboratory management. As testing volumes continue to increase alongside growing demands for rapid and reliable diagnostics, automation offers laboratories the capacity to sustain high-quality services while optimizing efficiency and resource utilization.

One of the most immediate advantages of automation lies in its ability to improve processing speed and reduce manual workload, particularly within high-volume laboratory environments. Automated systems streamline repetitive procedures and enable laboratory personnel to redirect their efforts toward higher-level responsibilities such as result validation, analyzer monitoring, and interpretation of clinically significant findings. Consequently, automation supports both operational efficiency and improved patient care by strengthening the reliability and timeliness of laboratory services [11,12].

Evidence from automated laboratories in Asia further demonstrates that productivity gains frequently accompany technological adoption. Experiences from tertiary healthcare facilities have shown that automation contributes to more efficient workflow organization and improved utilization of laboratory space and personnel, ultimately supporting higher

testing capacity and more sustainable operations [7]. These advantages are particularly relevant in laboratories facing increasing diagnostic demands and workforce pressures.

Economic considerations also represent a major factor driving automation adoption. Although advanced automated systems require substantial initial investment, economic evaluations suggest that long-term operational benefits may offset these costs through greater efficiency and optimized resource utilization. Total Laboratory Automation (TLA), in particular, has been associated with reductions in labor-intensive activities, improved reagent management, and lower operational waste, thereby generating favorable long-term returns on investment for healthcare institutions capable of supporting such systems [13,14]. Comparable evidence from Southeast Asia further supports this perspective. A recent health system-based cost-effectiveness analysis conducted in Singapore demonstrated that investment in robotic healthcare technologies can provide favorable long-term value when evaluated against conventional approaches, reinforcing the importance of considering automation as a strategic rather than purely financial decision [14]. From a management perspective, these findings reinforce the view that automation should be evaluated not solely as an expenditure but as an infrastructure investment capable of enhancing laboratory sustainability and productivity over time.

Beyond efficiency and cost considerations, automation increasingly incorporates artificial intelligence and robotics to strengthen diagnostic performance and workflow coordination. AI-supported systems facilitate faster data processing, enhance consistency in result interpretation, and reduce variability associated with manual procedures. Similarly, robotic technologies contribute to more standardized laboratory operations by performing repetitive and time-sensitive tasks with high precision and reproducibility. Such innovations allow laboratory professionals to concentrate on complex analytical reasoning and clinically relevant interpretation rather than routine manual activities, thereby improving both the quality and responsiveness of laboratory services [15].

Automation additionally plays an important role in improving quality assurance and patient safety by reducing errors occurring outside the analytical phase. Extra-analytical errors including specimen misidentification, labeling mistakes, and sample tracking failures remain significant contributors to diagnostic inaccuracy and compromised patient safety. Automated identification systems, barcode technologies, digital specimen tracking, and integrated laboratory information systems have demonstrated effectiveness in minimizing these risks while strengthening traceability and compliance with laboratory quality standards [16]. These technologies therefore support not only operational efficiency but also broader institutional goals related to safety, accreditation, and regulatory compliance.

Taken together, these operational, economic, and clinical advantages illustrate that laboratory automation represents more than a technical modernization effort. Rather, it constitutes a multidimensional strategy capable of improving diagnostic accuracy, workflow efficiency, patient safety, and long-term laboratory sustainability. Nevertheless, while the benefits of automation are increasingly evident in technologically advanced settings, translating these gains into diverse healthcare systems requires careful consideration of contextual readiness and implementation barriers issues particularly relevant to developing countries such as Indonesia.

3.3. Indonesia's Readiness and Implementation Challenges

Despite the transformative potential of laboratory automation, the readiness of Indonesia's laboratory system to adopt advanced automated technologies remains uneven. The implementation of automation occurs within a healthcare landscape characterized by considerable diversity in infrastructure, laboratory capacity, and resource availability across regions. Consequently, while automation presents important opportunities to

strengthen laboratory services, its adoption in Indonesia is shaped by a complex interaction of technological, financial, infrastructural, and policy-related constraints.

One of the most visible challenges concerns the uneven progress of laboratory digitalization across healthcare settings. Although digital laboratory systems and automated workflows are increasingly introduced in selected urban healthcare institutions, implementation remains limited in many primary healthcare facilities and rural regions. Studies examining healthcare digitalization in Indonesia indicate that disparities in infrastructure and technological readiness continue to influence the availability and quality of laboratory services, thereby constraining broader automation efforts [17]. Such variability creates an implementation landscape in which technological progress is concentrated within relatively well-resourced facilities while many laboratories continue to rely on semi-automated or manual systems.

Financial constraints further complicate automation adoption. Advanced laboratory automation, including robotic platforms and Total Laboratory Automation systems requires substantial capital investment, ongoing maintenance, software integration, and periodic equipment upgrades. For many healthcare facilities, particularly smaller laboratories and regional institutions operating under limited budgets, these financial requirements represent major barriers to implementation. Beyond acquisition costs, concerns regarding long-term sustainability and return on investment often influence institutional decision-making, resulting in cautious or delayed adoption of advanced systems [18]. These realities highlight that automation decisions are rarely determined by technological feasibility alone but are strongly shaped by organizational and economic considerations.

Workforce and infrastructure limitations represent additional barriers to sustainable implementation. Successful automation requires personnel capable of managing sophisticated instruments, maintaining digital systems, and ensuring quality assurance within increasingly complex laboratory environments. However, many laboratories, particularly in geographically remote or resource-constrained settings, continue to face shortages of personnel with specialized expertise in information technology, laboratory informatics, and automation-related quality management. Persistent disparities in electricity reliability, internet connectivity, digital infrastructure, and healthcare resources continue to limit automation readiness across many healthcare settings in Indonesia and other low- and middle-income countries [19]. Consequently, the adoption of automation cannot be separated from broader investments in laboratory infrastructure and human resource development.

Another critical concern relates to the regulatory and strategic environment surrounding automation adoption. Although Indonesia has established regulations governing laboratory practice and healthcare delivery, the integration of automation and robotics into laboratory medicine remains insufficiently supported by dedicated operational guidance and implementation frameworks. Laboratories may therefore face uncertainty regarding validation procedures, quality assurance standards, interoperability requirements, and accountability structures associated with increasingly automated systems. The absence of a unified national strategy specifically addressing laboratory automation risks is creating fragmented implementation patterns and widening disparities between facilities with differing institutional capacities.

These challenges intersect with a broader phenomenon increasingly described as the digital health divide. National evidence suggests that disparities in socioeconomic status, educational attainment, and geographic location continue to shape access to digital health services across Indonesia [20]. Such inequalities have important implications for laboratory automation, as populations served by under-resourced healthcare facilities may remain excluded from technological advances capable of improving diagnostic access and

quality. Without deliberate strategies promoting equitable implementation, automation may unintentionally reinforce existing healthcare inequalities rather than alleviate them.

Recent national initiatives nevertheless provide important opportunities for progress. Indonesia's digital health transformation agenda demonstrates growing policy recognition of the importance of technological integration within healthcare systems. Efforts to expand digital infrastructure and improve healthcare connectivity offer a potentially supportive foundation for future laboratory automation initiatives [21]. However, these ambitions must be accompanied by careful planning, investment in workforce readiness, and mechanisms ensuring equitable distribution of technological benefits across healthcare settings.

Taken together, these challenges illustrate that laboratory automation in Indonesia is not solely a matter of introducing advanced technologies into laboratory environments. Rather, it represents a broader systems-level issue involving infrastructure, financing, regulation, workforce preparedness, and health equity. Addressing these interconnected barriers will therefore be essential to ensuring that automation contributes meaningfully to strengthening laboratory services and improving healthcare access throughout Indonesia.

3.4. Workforce Transformation and the Evolving Role of Medical Laboratory Scientists (ATLM)

The expansion of laboratory automation and robotics has generated important changes in the professional landscape of medical laboratory practice, redefining not only laboratory workflows but also the competencies and responsibilities of medical laboratory scientists. In Indonesia, these developments have stimulated growing discussions regarding workforce readiness, professional identity, and the future role of *Ahli Teknologi Laboratorium Medik* (ATLM) within increasingly automated healthcare environments. While concerns regarding technological displacement persist, current evidence suggests that automation is more likely to transform rather than replace the profession, shifting professional responsibilities toward supervisory, analytical, and quality-oriented roles.

A central aspect of this transformation involves the changing competency profile required of laboratory professionals. As automated systems increasingly assume repetitive and technically standardized procedures, laboratory personnel are expected to develop stronger competencies in digital literacy, quality management, data interpretation, and oversight of automated processes. Emerging evidence from Indonesian laboratory settings indicates that workforce readiness for digital quality documentation and automated laboratory practices remains variable, highlighting the need for systematic competency development and structured adaptation strategies [22]. Consequently, technological advancement within laboratories should be accompanied by parallel investment in human capacity to ensure that automation strengthens rather than disrupts laboratory practice.

The evolving responsibilities of laboratory professionals observed in Indonesia reflect broader international trends. Contemporary competency frameworks increasingly position medical laboratory scientists as contributors not only to technical diagnostics but also to public health preparedness, laboratory leadership, communication, biosafety, and interdisciplinary collaboration. Global competency guidelines emphasize that laboratory professionals must be equipped to participate actively in laboratory management and public health systems while maintaining high standards of analytical quality and operational safety [23]. Such developments reinforce the view that laboratory medicine is evolving toward a more integrated and strategically important role within healthcare systems.

The implementation of Total Laboratory Automation (TLA) further illustrates this professional transition. Automated laboratories benefit from improved efficiency, reduced manual error, and streamlined workflow management; however, these gains are accompanied by changing workforce expectations. Rather than eliminating professional involvement, automation increasingly requires laboratory personnel capable of supervising automated

systems, troubleshooting technical problems, interpreting large volumes of laboratory data, and ensuring that automated outputs remain clinically valid and diagnostically meaningful. Case studies examining workforce experiences within automated laboratory environments demonstrate that automation shifts professional roles from predominantly manual functions toward higher-order responsibilities involving oversight, quality assurance, and systems management [24]. This transformation therefore requires continuous professional development and adaptability among laboratory professionals.

Within Indonesia, these evolving expectations remain closely tied to established professional and regulatory frameworks. National competency standards define ATLM responsibilities across diverse laboratory disciplines, including clinical pathology, microbiology, anatomical pathology, and molecular diagnostics, covering the entire testing process from pre-analytical preparation and specimen handling to analytical procedures, quality assurance, and laboratory management [25]. These standards underscore that laboratory practice encompasses not merely technical execution but also professional accountability and system-level responsibility. Importantly, Indonesian regulations governing laboratory practice further reinforce that laboratory services remain legally dependent upon qualified human professionals. ATLM practitioners are required to possess appropriate educational qualifications, professional registration, and practice licenses to conduct laboratory work legally, reflecting the state's commitment to maintaining professional oversight and diagnostic accountability [26].

The continuing importance of human oversight becomes particularly evident when automation is examined through practical implementation realities. Based on the authors' professional experience across Indonesian private hospitals, clinical laboratories, and community health centers (PUSKESMAS), considerable variability exists in automation readiness and technological integration across healthcare settings. Experiences across different healthcare settings illustrate considerable variability in automation readiness and technological integration. Large private hospitals may achieve efficient workflow coordination through integrated analyzers and centralized digital systems, whereas smaller laboratories and community health centers often continue to rely on semi-automated or manual processes due to financial and infrastructural limitations. Such differences highlight an important principle: automation does not eliminate the need for laboratory expertise but instead increases the importance of professional judgment in validating results, managing exceptions, and ensuring patient safety within diverse operational environments.

This principle is further reflected in discussions surrounding robotic technologies in pre-analytical procedures, including robotic phlebotomy. International developments demonstrate promising technical performance and potential efficiency gains, particularly within high-volume healthcare settings. Nevertheless, reflections on Indonesia's readiness for robotic venipuncture have emphasized persistent concerns involving regulatory preparedness, ethical considerations, professional accountability, and sociocultural acceptance [27]. These issues illustrate that technological feasibility alone does not guarantee successful implementation. Rather, automation must be introduced within frameworks capable of safeguarding patient welfare, clarifying legal responsibility, and maintaining professional standards.

The increasing integration of robotics into laboratory medicine further reinforces this evolving human–technology relationship. Over the last decade, robotic systems have become progressively involved in repetitive laboratory functions such as specimen transportation, aliquoting, and selected analytical procedures, contributing to improved precision and workflow standardization [28]. However, these developments simultaneously require laboratory professionals to acquire competencies related to system operation, maintenance, troubleshooting, and data management. The future laboratory workforce is therefore likely

to be defined not by competition between humans and machines but by collaboration in which automation enhances efficiency while trained professionals preserve diagnostic integrity and clinical relevance.

Taken together, these developments demonstrate that the future role of ATLM in Indonesia extends beyond traditional technical practice toward increasingly strategic responsibilities involving automation oversight, digital competency, laboratory management, and interdisciplinary collaboration. Rather than diminishing professional relevance, automation highlights the enduring necessity of qualified human expertise to ensure that technological innovation remains safe, accountable, and aligned with patient-centered healthcare.

3.5. Toward Equitable Laboratory Automation in Indonesia: A Proposed Roadmap

The challenges identified across infrastructure, regulation, workforce capacity, and governance underscore the need for a structured national strategy. Figure 2 presents a conceptual framework illustrating how these four interrelated domains collectively support equitable laboratory automation in Indonesia, while the corresponding implementation priorities are summarized in Table 2.

Indonesia's ongoing healthcare transformation presents an important opportunity to position laboratory automation and robotics as integral components of national health system strengthening. The Ministry of Health has articulated an ambitious reform agenda through six strategic transformation pillars, including the pillar of health technology transformation aimed at accelerating digital integration, improving healthcare connectivity, and modernizing biomedical services [29]. Within this policy landscape, laboratory automation should be viewed not merely as an isolated technological advancement but as a strategic infrastructure investment capable of supporting more efficient, standardized, and equitable diagnostic services.

However, realizing this potential requires a deliberate and context-sensitive implementation strategy. Automation adoption in Indonesia cannot rely solely on technology procurement or market-driven expansion. Instead, successful integration requires a coordinated national roadmap capable of addressing the interconnected challenges of infrastructure, regulation, workforce preparedness, and healthcare equity identified throughout this review.

A first priority involves strengthening regulatory and governance frameworks surrounding laboratory automation and robotics. Although Indonesia possesses regulations governing laboratory practice and professional responsibility, dedicated operational guidance addressing increasingly automated laboratory systems remains limited. Clear policies are therefore needed to establish standards for clinical validation, interoperability, quality assurance, cybersecurity, and accountability within automated laboratory environments. Such frameworks are particularly important in clarifying legal responsibility when automated processes contribute to diagnostic decision-making or operational failures. Regulatory clarity will not only protect patients and laboratory professionals but also provide greater confidence for institutions considering technological investment.

Equally critical is sustained investment in human capital. The transition toward automated laboratories demands a workforce equipped with competencies extending beyond conventional laboratory techniques. As discussed previously, future ATLM practice increasingly requires proficiency in digital systems, automation oversight, troubleshooting, quality management, and data interpretation. Consequently, educational institutions and professional organizations should collaborate to modernize ATLM curricula by incorporating laboratory automation, robotics, laboratory informatics, and digital quality systems into competency-based training. In parallel, structured continuing professional development and certification pathways are needed to ensure that the existing workforce can adapt to technological change without professional marginalization.

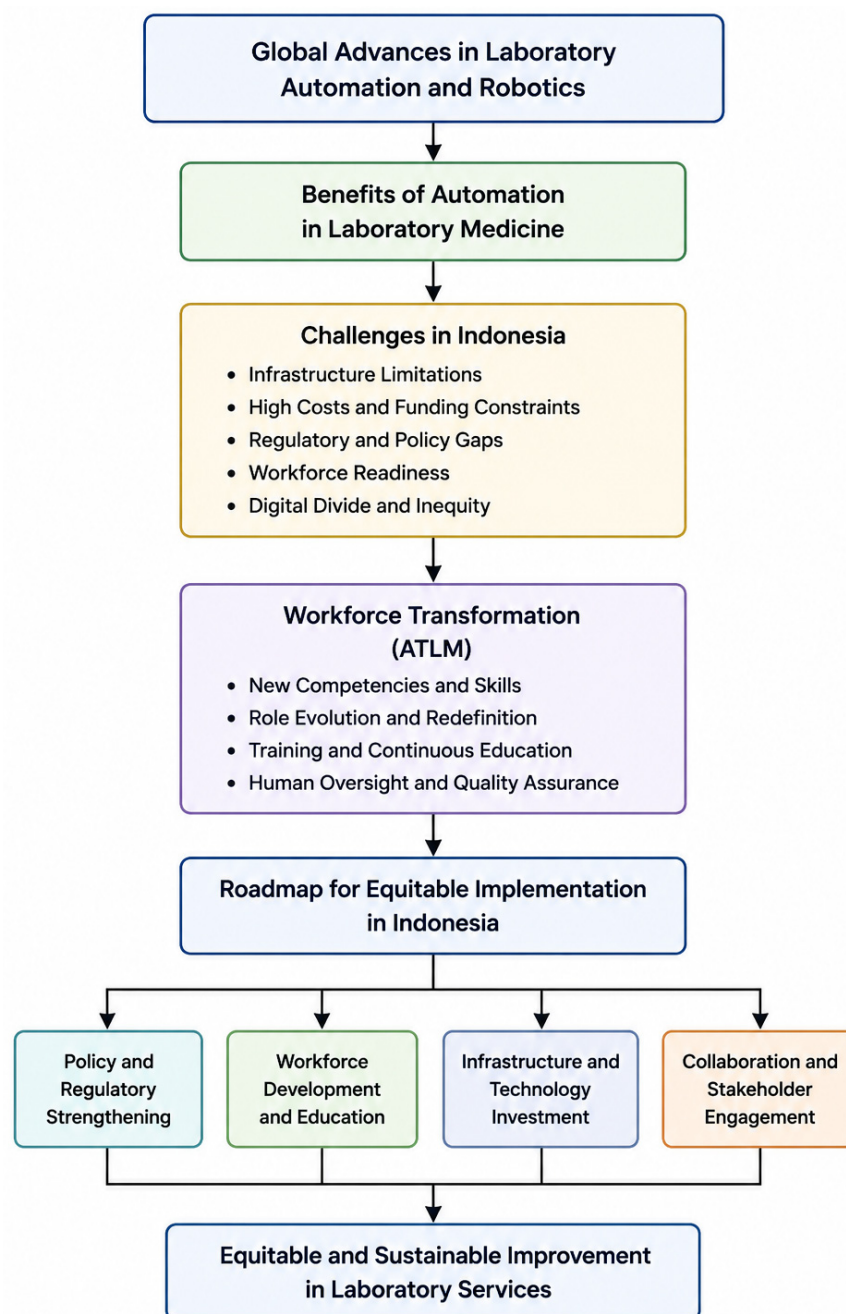


Figure 2. Proposed Roadmap for Equitable Laboratory Automation in Indonesia.

Infrastructure development represents another essential component of equitable implementation. Persistent disparities in electricity reliability, internet access, laboratory design, and digital connectivity continue to limit automation readiness across many healthcare settings. A uniform nationwide deployment strategy may therefore be impractical and economically inefficient. Instead, a phased implementation model may offer a more realistic pathway, prioritizing high-volume referral laboratories and tertiary facilities while gradually expanding digital integration and automation capacity in regional and primary healthcare laboratories. Such an approach would allow policymakers to balance innovation with feasibility while minimizing the risk of widening regional disparities.

Pilot implementation programs may further support evidence-informed policy development. Carefully selected pilot laboratories could serve as demonstration sites for evaluating operational feasibility, cost-effectiveness, workforce adaptation, and regulatory requirements before broader deployment. Experiences generated through these initiatives

would provide valuable local evidence to guide future investment decisions and refine implementation strategies suited to Indonesia's healthcare realities.

Table 2. Proposed Roadmap for Laboratory Automation Implementation in Indonesia.

Domain	Current Issues	Recommended Actions	Key Stakeholders	Indicators
Infrastructure	Unequal readiness across regions	Phased deployment beginning with tertiary laboratories	Ministry of Health, hospitals, local governments	Increased automation coverage and digital connectivity
Regulation	Limited automation-specific operational guidance	Develop national laboratory automation framework and validation standards	Ministry of Health, professional organizations	Publication of national technical guidelines
Workforce	Digital competency gaps among ATLM personnel	Curriculum reform and continuing professional development programs	Universities, ATLM associations, Ministry of Education	Number of certified personnel trained in automation systems
Governance	Fragmented implementation and limited coordination	Strengthen multi-stakeholder collaboration and pilot implementation programs	Government, academia, healthcare industry	Number of pilot laboratories and national collaborative programs

Finally, equitable laboratory automation will depend upon sustained multi-stakeholder collaboration. Government institutions, professional associations, academic organizations, healthcare providers, and technology industries must work together to ensure that automation strategies remain responsive to national priorities and local operational realities. Such collaboration is essential not only for technological development but also for maintaining public trust, ensuring ethical implementation, and promoting socially responsible innovation.

Taken together, these considerations suggest that Indonesia's pathway toward laboratory automation should not be framed as a simple transition from manual to automated systems. Rather, it should be understood as a broader process of laboratory system transformation requiring strategic governance, workforce development, infrastructure investment, and equity-centered planning. If implemented thoughtfully, automation and robotics hold considerable potential not only to modernize laboratory services but also to strengthen diagnostic quality, expand healthcare access, and contribute meaningfully to Indonesia's long-term health system resilience.

3.6. Limitations

This review has several limitations. First, as a structured narrative review, the study was not intended to provide exhaustive systematic evidence synthesis or quantitative meta-analysis. Although selected PRISMA principles were adopted to improve transparency, the review remains interpretive in nature and may be subject to selection bias. Second, several discussions relied on the international literature due to the limited availability of Indonesian empirical studies specifically addressing laboratory automation and robotics. Third, the inclusion of professional experiences from the authors may introduce contextual interpretation influenced by local practice environments. Nevertheless, these perspectives were incorporated solely to enrich understanding of practical implementation challenges within Indonesian healthcare settings.

4. Conclusions

Laboratory automation and robotics are increasingly reshaping laboratory medicine by improving operational efficiency, diagnostic accuracy, quality assurance, and patient safety. Global advances in automation, artificial intelligence, and integrated laboratory systems demonstrate substantial potential to strengthen laboratory services and support more responsive healthcare delivery. However, translating these benefits into the Indonesian context remains a complex undertaking shaped by infrastructural disparities, financial limitations, workforce readiness, and evolving regulatory environments.

This review highlights that the successful integration of automation in Indonesia depends not solely on technological availability but on broader health system preparedness. Persistent inequalities in digital infrastructure and laboratory capacity risk limiting equitable access to technological innovation if implementation occurs without strategic planning and policy coordination. Equally important, the transformation of laboratory practice reinforces, rather than diminishes the role of medical laboratory scientists (ATLM), whose responsibilities are increasingly expanding toward automation oversight, data interpretation, quality management, and interdisciplinary collaboration.

Accordingly, the future of laboratory automation in Indonesia should be approached through an equity-centered and systems-oriented framework. Strengthening regulatory governance, modernizing workforce competencies, investing in digital and laboratory infrastructure, and fostering collaboration among government, academia, professional organizations, and industry will be essential to ensuring sustainable implementation. Through thoughtful planning and responsible innovation, laboratory automation and robotics hold significant potential not only to modernize laboratory services but also to support Indonesia's broader health transformation agenda and strengthen equitable access to high-quality diagnostic care.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Omair, A.; Jabbar, A.M.A.; Albulushi, M.O. Recent advancements in laboratory automation technology and their impact on scientific research and laboratory procedures. *Int. J. Health Sci.* **2023**, *7*, 3043–3052. [\[CrossRef\]](#)
2. Gudi, N.; Raj, E.A.; Jahn, B.; Siebert, U.; Brand, A. Evaluations of digital public health interventions in the WHO Southeast Asia region: A systematic literature review. *Int. J. Technol. Assess. Health Care* **2024**, *40*, e78. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Forslund, M.; Mathieson, K.; Djibo, Y.; Mbindyo, C.; Lugangira, N.; Balasubramaniam, P. Strengthening the evidence base on the use of digital health technologies to accelerate progress towards universal health coverage. *Oxf. Open Digit Health* **2024**, *2*, oqae033. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Greenhalgh, T.; Thorne, S.; Malterud, K. Time to challenge the spurious hierarchy of systematic over narrative reviews? *Eur. J. Clin. Investig.* **2018**, *48*, e12931. [\[CrossRef\]](#)
5. Ferrari, R. Writing narrative style literature reviews. *Med. Writ.* **2015**, *24*, 230–235. [\[CrossRef\]](#)
6. Alyami, A.A.; Alaqil, N.M.; Alsulayyim, A.S.M.; Al Yami, R.M.K.; Salem, F.J.M.; Al Hatailah, A.M.H.; Al Zandan, S.A.; Al Mushref, S.A.N.; Musharraf, S.A.N.A.L.; Balharith, A.S. Comprehensive review of laboratory automation, quality control, and workforce adaptation. *J. Ecohumanism* **2024**, *3*, 5548–5557. [\[CrossRef\]](#)
7. Yeo, C.P.; Ng, W.Y. Automation and productivity in the clinical laboratory: Experience of a tertiary healthcare facility. *Singap. Med. J.* **2018**, *59*, 597–601. [\[CrossRef\]](#)
8. Er, T.K. Implementation of an advanced automation system in the laboratory medicine department. *Clin. Lab.* **2025**, *71*, 967. [\[CrossRef\]](#) [\[PubMed\]](#)

9. Alabdali, D.H.; Alsolami, E.A.; AlSehli, O.O.; Aldawsari, H.H.; Alzain, B.M.; Yamani, O.F.; Alsharif, R.N.; Endergiri, D.I.M.; AL-Harthi, A.S.; Alamoudi, A.H. Advancing laboratory medicine: A review of emerging technologies and their impact on diagnostic accuracy and efficiency. *J. Ecohumanism* **2024**, *3*, 1699–1703. [\[CrossRef\]](#)
10. Yu, H.E.; Lanzoni, H.; Steffen, T.; Derr, W.; Cannon, K.; Contreras, J.; Olson, J.E. Improving laboratory processes with total laboratory automation. *Lab. Med.* **2019**, *50*, 96–102. [\[PubMed\]](#)
11. Kementerian Kesehatan RI. *Transformasi Layanan Laboratorium Dalam Rangka Reformasi Kesehatan*; Kementerian Kesehatan: Jakarta, Indonesia, 2021.
12. World Health Organization. *Laboratory Quality Management System Handbook*; WHO Press: Geneva, Switzerland, 2020.
13. Kim, K.; Lee, S.G.; Kim, T.H.; Lee, S.G. Economic evaluation of total laboratory automation in the clinical laboratory of a tertiary care hospital. *Korean J. Lab. Med.* **2022**, *42*, 89–95. [\[CrossRef\]](#)
14. Shankar, R.; Tang, N.; Shafawati, N.; Phan, P.; Mukhopadhyay, A.; Chew, E. Cost-effectiveness analysis of robotic exoskeleton versus conventional physiotherapy for stroke rehabilitation in Singapore from a health system perspective. *BMJ Open* **2025**, *15*, e095269. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Sawanni, R.; Mathur, M.; Gupta, R.; Kumar, A.; Richa; Garg, A. The performance analysis of health care automation using artificial intelligence model. In Proceedings of the 2024 International Conference on Communication, Computer Sciences and Engineering (IC3SE), Gautam Buddha Nagar, India, 9–11 May 2024; pp. 990–994. [\[CrossRef\]](#)
16. Bakan, E.; Bakan, N. Prevention of extra-analytical phase errors by non-analytical automation in clinical laboratory. *Turk. J. Biochem.* **2021**, *46*, 235–243. [\[CrossRef\]](#)
17. Putra, A.; Harahap, H. Implementasi digitalisasi laboratorium di layanan kesehatan primer. *J. Adm. Kesehat. Indones.* **2021**, *9*, 23–30.
18. Odigie, E.B.; Obiagba, M.C. Medical laboratory robotics: The positive and negative implications in developing countries. *Ann. BioMed. Sci.* **2019**, *18*, 35–46.
19. World Health Organization. *Global Strategy on Digital Health 2020–2025*; World Health Organization: Geneva, Switzerland, 2021.
20. Nababan, H. Digital health divide in Indonesia: Evidence from national-level data. *Eur. J. Public Health* **2024**, *34*, ckae144.426. [\[CrossRef\]](#)
21. United Nations Development Programme. Indonesia Launches Blueprint for Digital Health to Expand Inclusive Health Care Coverage [Internet]. UNDP. 2023. Available online: <https://www.undp.org/indonesia/press-releases/indonesia-launches-blueprint-digital-health-expand-inclusive-health-care-coverage> (accessed on 30 June 2025).
22. Sari, N.; Widodo, S.; Arifin, R. Kesiapan SDM laboratorium terhadap dokumentasi mutu digital. *J. Teknol. Lab.* **2022**, *11*, 45–52.
23. Ned-Sykes, R.; Johnson, C.; Ridderhof, J.C.; Perlman, E.; Pollock, A.; DeBoy, J.M.; Centers for Disease Control and Prevention (CDC). Competency guidelines for public health laboratory professionals. *MMWR Suppl.* **2015**, *64*, 1–16. [\[PubMed\]](#)
24. Al Naam, Y.A.; Elsafi, S.; Al Jahdali, M.H.; Al Shaman, R.S.; Al-Qurouni, B.H.; Al Zahrani, E.M. The impact of total automaton on the clinical laboratory workforce: A case study. *J. Healthc. Leadersh.* **2022**, *14*, 55–62. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Kementerian Ketenagakerjaan Republik Indonesia. *Keputusan Menteri Ketenagakerjaan Republik Indonesia Nomor 170 Tahun 2018 Tentang SKKNI Bidang Teknologi Laboratorium Medik*; Kementerian Ketenagakerjaan: Jakarta, Indonesia, 2018.
26. Kementerian Kesehatan Republik Indonesia. *Peraturan Menteri Kesehatan Nomor 42 Tahun 2015 Tentang Izin dan Penyelenggaraan Praktik Ahli Teknologi Laboratorium Medik*; Kementerian Kesehatan RI: Jakarta, Indonesia, 2015.
27. Andaria, A. Is Indonesia ready for robotic phlebotomy? A reflection on technology, ethics, and readiness in clinical laboratories. *J. Robot Surg.* **2025**, *19*, 333. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Ejime, E.; Enebeli, C.P.; Obomhense, E.; Nandom, B.; Elueme, E.A.; Amanze, U.C. The role of robots in laboratory medicine in the last decade (2014–2024): A narrative review. *IOSR J. Dent. Med. Sci.* **2024**, *23*, 29–34. [\[CrossRef\]](#)
29. Kementerian Kesehatan RI; Biro Komunikasi dan Pelayanan Publik. *Buku Kinerja Kementerian Kesehatan Republik Indonesia Tahun 2022–2023: Transformasi Kesehatan Mewujudkan Masyarakat Indonesia Sehat Dan Unggul*; Kementerian Kesehatan RI: Jakarta, Indonesia, 2024.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.