

SMART LABORATORY MANAGEMENT: DIGITAL TECHNOLOGY INTEGRATION FOR 21ST-CENTURY SCIENCE LEARNING

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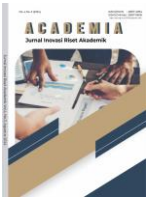
ABSTRAK

Perkembangan teknologi digital mendorong transformasi pengelolaan laboratorium IPA menuju sistem yang lebih modern, efektif, dan adaptif terhadap kebutuhan pembelajaran abad 21. Penelitian ini bertujuan untuk mendeskripsikan implementasi Smart Laboratory Management berbasis teknologi digital dalam mendukung pembelajaran IPA yang berorientasi pada keterampilan abad 21. Kebaruan penelitian ini terletak pada kajian terpadu yang menganalisis implementasi Smart Laboratory Management sebagai sistem tunggal yang secara simultan mengintegrasikan tata kelola laboratorium digital dan pengembangan keterampilan abad 21 peserta didik, khususnya dalam konteks madrasah dan sekolah menengah di Indonesia suatu perspektif yang belum secara komprehensif dikaji dalam penelitian sebelumnya. Penelitian menggunakan pendekatan kualitatif dengan jenis studi kasus. Lokasi penelitian dilakukan pada laboratorium IPA di tingkat madrasah/sekolah menengah. Teknik pengumpulan data dilakukan melalui observasi, wawancara mendalam, dan dokumentasi. Informan penelitian terdiri atas kepala laboratorium, guru IPA, laboran, dan peserta didik. Analisis data menggunakan model Miles dan Huberman yang meliputi reduksi data, penyajian data, dan penarikan kesimpulan. Hasil penelitian menunjukkan bahwa implementasi Smart Laboratory Management dilakukan melalui digitalisasi administrasi laboratorium, penggunaan barcode inventaris, pemanfaatan aplikasi pengelolaan alat dan bahan, serta integrasi media pembelajaran digital dalam kegiatan praktikum. Sistem ini mampu meningkatkan efektivitas pengelolaan laboratorium, mempercepat akses informasi inventaris, meningkatkan keterampilan kolaborasi dan literasi digital peserta didik, serta mendukung pembelajaran IPA berbasis keterampilan abad 21. Kendala implementasi meliputi keterbatasan infrastruktur teknologi, kompetensi digital tenaga laboratorium, dan keterbatasan anggaran pengembangan sistem. Penelitian ini memberikan implikasi bahwa transformasi laboratorium berbasis teknologi digital menjadi kebutuhan penting dalam meningkatkan mutu pembelajaran IPA modern.

Kata Kunci: *smart laboratory*, manajemen laboratorium, teknologi digital, pembelajaran IPA, keterampilan abad 21

ABSTRACT

The advancement of digital technology is driving the transformation of science laboratory management toward a more modern, effective, and adaptive system aligned with the demands of 21st-century learning. This study aims to describe the implementation of digital technology-based Smart Laboratory Management in supporting science learning oriented toward 21st-century skills. The novelty of this study lies in its integrated analysis of Smart Laboratory Management implementation as a unified system that simultaneously integrates digital laboratory governance and the development of students' 21st-century skills, particularly within the context of madrasas and secondary schools in Indonesia a perspective that has not been comprehensively examined in prior research. The study employed a qualitative approach using a case study design. The research was conducted at science laboratories in madrasas and



secondary schools. Data were collected through observation, in-depth interviews, and documentation. Research informants consisted of laboratory heads, science teachers, laboratory technicians, and students. Data analysis followed the Miles and Huberman model, encompassing data reduction, data display, and conclusion drawing. The findings indicate that Smart Laboratory Management was implemented through the digitalization of laboratory administration, the use of inventory barcodes, the utilization of equipment and materials management applications, and the integration of digital learning media into practicum activities. This system was capable of enhancing laboratory management effectiveness, accelerating access to inventory information, improving students' collaboration skills and digital literacy, and supporting 21st-century skills-based science learning. Implementation challenges included limitations in technological infrastructure, the digital competence of laboratory staff, and budget constraints for system development. This study implies that digital technology-based laboratory transformation is an essential requirement for improving the quality of modern science learning.

Keywords: smart laboratory, laboratory management, digital technology, science learning, 21st-century skills

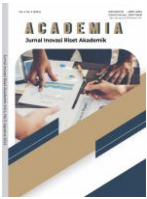
INTRODUCTION

The development of digital technology in the era of the industrial revolution 4.0 has brought major changes in various aspects of life, including in the field of education. Educational transformation does not only occur in the learning process in the classroom, but also in the management system of educational facilities, including science laboratories. The science laboratory has a strategic role as a center for experimentation, observation, and scientific skill development of students. In the context of modern learning, laboratories are no longer seen as just a place for practicums, but rather an innovation space that is able to integrate digital technology to support the development of 21st century skills (Zulfa & Adam Malik, 2025).

Science learning in the 21st century requires students to have the ability to think critically, creatively, communicate, collaborate, and digital literacy (Zulfa & Adam Malik, 2025). These skills are the main need in dealing with increasingly complex scientific and technological developments. Therefore, the science learning system needs to be supported by effective, efficient, and digital technology-based laboratory management in order to be able to create learning experiences that are relevant to the needs of the times (Anggraini et al., 2025).

However, the condition of the management of science laboratories in various schools and madrasas is still facing various problems (Setiya Rini et al., 2024). Many laboratories still use a manual administration system in managing an inventory of tools and practicum materials. Data collection of laboratory equipment is generally still carried out through conventional inventory books so that it often causes problems such as data loss, mismatches in the amount of inventory, delays in finding tools, and suboptimal monitoring of the condition of tools and materials. In addition, the administrative process of borrowing laboratory equipment that is still manual causes laboratory services to be less effective and take a relatively long time (Choerudin, 2021).

Another problem that is often found is the limited integration of digital technology in science practicum activities. Some laboratories have not utilized digital applications, barcode systems, or technology-based inventory monitoring systems (M. N., 2024). In fact, the development of information technology allows laboratory management to be carried out in a more modern way through a digital system that is able to increase data efficiency and accuracy. The unpreparedness of laboratories in facing digital transformation can have an impact on the



low quality of science practicum learning and the lack of optimal 21st century skill development of students (Atchia & Rumjaun, 2023).

In facing these challenges, the concept of Smart Laboratory Management is one of the relevant innovations to be applied to the management of science laboratories (Xu et al., 2024). Smart Laboratory Management is a laboratory management system based on digital technology that integrates various components such as digital inventory, barcode system, laboratory monitoring applications, inventory databases, and digital learning media (Schalcher et al., 2025). This system aims to increase the effectiveness of laboratory management, facilitate access to inventory information, accelerate laboratory administration, and support more interactive and technology-based science learning.

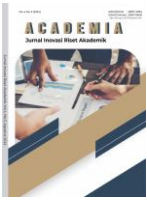
The implementation of Smart Laboratory Management is also closely related to the concept of digital technology-based education and society 5.0. In the era of society 5.0, technology is not only used as an administrative tool, but also an integral part of creating a learning system that is intelligent, adaptive, and student-centered (Hakim et al., 2026). The use of digital technology in science laboratories allows students to gain a more contextual learning experience through the integration of interactive media, digital simulations, application-based data processing, and a more modern practicum system.

In addition to improving the quality of learning, Smart Laboratory Management can also help schools in improving laboratory governance professionally. The digital inventory system allows laboratory heads and laboratory workers to monitor tools and materials in real-time, making it easier to control the use of the laboratory (Agesi et al., 2025). The use of barcodes in laboratory equipment is also able to reduce the risk of losing inventory and increase the accuracy of laboratory data (Mardhatillah Febiana, 2025). Thus, laboratory management becomes more transparent, effective, and efficient.

Several previous studies have shown that laboratory digitization is able to increase the effectiveness of laboratory management and the quality of practicum learning (Haristian et al., 2025). Research on the use of barcode-based inventory systems shows an increase in the speed of administration and ease of management of laboratory equipment. Other research also explains that the integration of digital technology in science learning can increase students' learning motivation, critical thinking skills, and digital literacy (Dana, 2025). However, research that specifically discusses the implementation of Smart Laboratory Management based on digital technology in supporting skill-oriented science learning in the 21st century is still relatively limited, especially in the context of madrasas and secondary schools. Unlike prior studies that separately examined either laboratory digitization or 21st century skill development, no previous research has comprehensively examined the integrated implementation of a digital technology-based Smart Laboratory Management system as a unified framework that simultaneously enhances laboratory governance and cultivates 21st century competencies particularly within the institutional context of madrasas and secondary schools. The present study directly addresses this gap.

Based on these conditions, this research is important to describe the implementation of Smart Laboratory Management based on digital technology in supporting 21st century skill-oriented science learning. This research not only focuses on the use of technology in laboratory management, but also analyzes its impact on the effectiveness of science learning and the development of students' skills. In addition, this study also identifies supporting factors and obstacles to the implementation of Smart Laboratory Management in schools and madrasas.

The results of this research are expected to make a theoretical and practical contribution to the development of laboratory management based on digital technology. Theoretically, this



research can enrich the study of the integration of digital technology in the management of educational laboratories. Practically, the results of the research can be a reference for schools, madrasas, science teachers, laboratories, and education managers in developing a more modern laboratory system and in accordance with the demands of 21st century learning.

RESEARCH METHODOLOGY

This study employed a qualitative approach using a case study design (Syahrizal & Jailani, 2023). The research was conducted at the science laboratory of MTsN 1 Kota Palu, which was purposively selected because the school had implemented several digital-based laboratory management systems, including barcode inventory and digital laboratory administration.

The research subjects consisted of laboratory heads, science teachers, laboratory assistants, and students who were directly involved in the implementation of the Smart Laboratory Management system. Informants were selected purposively based on their active involvement in laboratory management and digital-based practicum activities.

Data collection techniques included observation, semi-structured interviews, and documentation. Observations were conducted to examine the implementation of digital laboratory systems in inventory management, barcode utilization, laboratory administration, and science practicum learning activities. Semi-structured interviews were used to obtain in-depth information regarding the effectiveness of the system, its benefits, implementation challenges, and its contribution to 21st-century skills development. Documentation was carried out by collecting laboratory inventory records, digital application data, practicum reports, and photographs of laboratory activities.

Data analysis employed the Miles and Huberman interactive model, which includes data reduction, data display, and conclusion drawing (Qassimi, 2023). In addition, the analysis process involved data coding, categorization, and theme identification to interpret the findings comprehensively. The validity of the data was ensured through source triangulation and technique triangulation by comparing the results of observations, interviews, and documentation. All participants were informed about the purpose of the study, and interviews were conducted with participants' consent.

RESULT AND DISCUSSION

Result

Implementasi Smart Laboratory Management

The implementation of Smart Laboratory Management is carried out through several main stages, namely digitization of laboratory administration, the use of barcodes for equipment and material inventory, and the integration of laboratory management applications.

Table 1. Smart Laboratory Management Implementation

No	Implementation Components	Description	Field Findings / Empirical Evidence
1	Inventory Digitization	Use of digital databases for recording tools and materials	Laboratory inventory data have been stored digitally using spreadsheet-based applications, making data retrieval faster and minimizing recording errors.
2	Barcode System	Identification of laboratory tools using barcodes	Each laboratory tool is equipped with a barcode label to facilitate

No	Implementation Components	Description	Field Findings / Empirical Evidence
3	Monitoring Laboratory	Digital monitoring of the use of tools and materials	identification, borrowing, and return processes during practicum activities. Laboratory heads and assistants can monitor the condition and usage of tools in real-time through digital inventory applications.
4	Digital Learning Media	Integration of practicum videos and science simulations	Teachers use digital simulations and practicum videos during laboratory activities to support students' understanding of scientific concepts.
5	Automated Reporting	Recap of the use of system-based laboratories	Laboratory usage reports and inventory recapitulations are generated automatically through the digital management system, reducing manual administrative workload.

The results of observations show that the use of barcodes simplifies the process of finding laboratory tools and accelerates inventory data collection. Teachers and laboratory workers can find out the condition of the tool in real-time through the digital application used.

Impact on Science Learning

The implementation of Smart Laboratory Management has a positive impact on science learning. Students become more active in practicum and have better digital literacy skills.

Table 2. The Impact of Implementation on 21st Century Skills

Skills	Implementation Impact	Empirical Evidence / Interview Findings
Critical Thinking	Students are more active in analyzing practicum data	Science teachers explained that students previously tended to wait for instructions during practicum activities, while after the implementation of digital systems, students became more active in interpreting experimental results independently.
Collaboration	Practicum is carried out collaboratively based on digital systems	Students worked in groups using digital laboratory applications to record and share practicum results, which improved teamwork during experiments.
Communication	Presentation of practicum results using digital media	Students presented practicum findings using presentation applications and digital reports, making classroom discussions more interactive.
Creativity	Students create innovative practicum reports	Teachers reported that students began designing more creative practicum reports by integrating images, graphs, and digital visualization tools.
Digital Literacy	Students are accustomed to using laboratory technology	Students became familiar with barcode scanning systems, digital inventory applications, and virtual laboratory simulations during science practicum activities.

In addition, science teachers stated that the laboratory's digital system helps learning efficiency because the administrative process and practicum preparation are faster.

Implementation Constraints

Although Smart Laboratory Management provides many benefits, its implementation still faces several obstacles. Based on the interview and observation results, the constraints and the school's responses are described as follows:

1. Limitations of laboratory technology devices

Some laboratory equipment supporting the digital system, such as computers, barcode scanners, and LCD projectors, were still limited in number. As a result, the implementation of the digital system could not be fully optimized during practicum activities. A laboratory assistant stated:

“Sometimes we have to use the devices alternately because the number of computers and barcode scanners is still limited.”

To address this issue, the school gradually procures supporting technology devices and maximizes the use of available facilities during laboratory activities.

2. Uneven digital competence of laboratory personnel

Not all laboratory staff and teachers had adequate skills in operating digital laboratory systems and applications. Some teachers still experienced difficulties in managing digital inventory and utilizing virtual laboratory media.

A science teacher explained:

“At the beginning, some teachers were still confused about using the digital inventory application because they were more familiar with manual administration.”

In response, the school organized internal training and mentoring programs to improve teachers' and laboratory assistants' digital competencies.

3. Limited budget for system development

The implementation of Smart Laboratory Management requires financial support for application development, internet access, and maintenance of digital devices. Budget limitations became one of the major challenges in sustaining the system.

The head of the laboratory mentioned:

“The development of digital laboratory systems requires considerable funding, especially for maintenance and software updates.”

To overcome this constraint, the school prioritized essential technology needs and sought support through school operational funds and institutional cooperation programs.

4. The school internet network is not optimal

Internet connectivity problems occasionally disrupted access to digital applications and online practicum resources. This condition affected the effectiveness of digital laboratory activities.

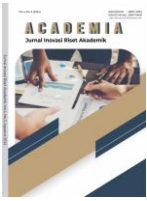
One student stated:

“Sometimes the practicum process is interrupted when the internet connection becomes unstable.”

As a solution, the school attempted to improve network infrastructure and provided offline digital learning materials that could still be accessed during network disruptions.

Discussion

The findings of this study demonstrate that the effectiveness gains observed in Smart Laboratory Management implementation are not simply attributable to the introduction of technology per se, but rather to the structural replacement of error-prone manual workflows with integrated digital systems. This distinction is theoretically important: it aligns with the sociotechnical systems perspective, which holds that technology produces meaningful change



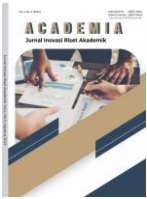
only when it is embedded within reorganized social and organizational practices (Hartono, 2024). The shift from manual inventory books to real-time barcode-based databases, for instance, eliminates a class of systematic errors rooted in human cognitive limitations not merely speed which explains why the administrative gains in this study were qualitative as well as quantitative.

The effectiveness of barcode-based inventory digitization in this study is consistent with, yet contextually extends, findings reported by Elec et al. (2025), who demonstrated that barcode systems reduced tool misidentification and borrowing queue delays at the aeronautics laboratory of PhilSCA, Philippines. However, a critical difference emerges: while Elec et al. operated in a single-purpose technical laboratory with relatively homogeneous equipment, this study was conducted in science laboratories that manage diverse biological, chemical, and physics tools simultaneously. The successful implementation in this more complex context suggests that barcode systems possess broader scalability than previously documented. Furthermore, unlike Jadhav (2024), whose Lab Inventory Management System (LIMS) focused solely on encoding item name, quantity, and expiration dates for research institutions, the present study found that barcode integration in school laboratories also served a pedagogical function students developed awareness of systematic inventory control as part of their practicum experience, an outcome Jadhav's industrial-oriented framework did not address.

The use of a barcode system also provides convenience in monitoring the use of laboratory equipment. Laboratory heads and laboratory workers can find out the status of equipment usage, the amount of inventory, and the condition of the equipment in real-time through the laboratory management application. These findings show that inventory digitization is able to increase transparency and accountability of laboratory management. In addition, the digital system helps reduce the risk of losing tools and speeds up the process of borrowing and returning practicum tools. This real-time monitoring capability addresses what Kubanova et al. (2022) identified as the "visibility gap" in conventional inventory systems, where decision-makers lack timely data to prevent equipment shortages before they disrupt learning activities. Critically, the present study found that this visibility improvement was most pronounced for perishable laboratory materials chemicals and biological specimens where delayed detection of shortages had previously caused practicum cancellations. This finding points to a practically significant implication: digital inventory systems in science education should prioritize expiry-date tracking modules as a core feature, not an optional add-on.

Theoretically, these findings contribute to the growing body of literature on laboratory digitalization in educational settings. Hartono (2024), in a study of digital laboratory development at Universitas Negeri Malang, found that digitized laboratories functioned as more accessible and efficient learning resources within a Society 5.0 framework. The present study corroborates and extends this by demonstrating that the Society 5.0 logic where technology serves human-centered ends is operationalizable at the secondary school and madrasah level, not only in higher education. This is a meaningful contextual contribution, given that most existing literature on smart laboratory management is concentrated in university or industrial settings, leaving a documented gap for secondary and religious school contexts (Jadhav, 2024; Elec et al., 2025).

In addition to having an impact on the laboratory management aspect, the implementation of Smart Laboratory Management also affects the quality of science learning. The use of digital learning media in practicum activities makes the learning process more interesting and interactive. Science teachers use practicum videos, virtual simulations, and digital applications to support experimental activities in the laboratory (Yanti et al., 2023). This



helps students understand the concept of science in a more concrete and contextual way. The mechanism underlying this improvement can be explained through dual-coding theory: when abstract scientific concepts are simultaneously represented through verbal instruction and visual digital simulations, students construct richer cognitive schemas than through either modality alone. This theoretical explanation accounts for why digital media integration did not merely supplement conventional practicum, but qualitatively changed the depth of conceptual understanding students could achieve a distinction that prior descriptive studies on educational technology use (Yanti et al., 2023) have not systematically theorized.

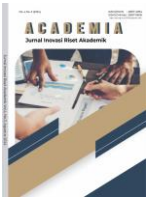
The shift from procedural to inquiry-based participation in digital practicum activities observed in this study merits specific comparison with Hartono's (2024) findings on digital laboratory effectiveness, which reported improved accessibility but did not measure changes in student agency or participation quality. The present study advances beyond accessibility metrics by demonstrating that digital laboratory environments alter the epistemic role of students: from passive executors of prescribed procedures to active analysts who interrogate data and construct interpretations. This finding aligns with constructivist learning theory, particularly Vygotsky's emphasis on the role of mediating tools in cognitive development here, digital applications serve as mediating artifacts that scaffold higher-order thinking during practicum activities.

From the aspect of 21st century skills, the implementation of Smart Laboratory Management contributes to the development of students' critical thinking, collaboration, communication, creativity, and digital literacy skills. In practicum activities, students are required to work together in groups, discuss the results of experiments, and present the results of the practicum using digital media. These activities indirectly train students' scientific communication and collaboration skills. It is important to note, however, that this study identified a gradient in skill development: collaboration and digital literacy showed the most salient growth, while creativity and critical communication remained more dependent on the individual teacher's pedagogical approach. This gradient suggests that Smart Laboratory Management, as an infrastructure, creates necessary but not sufficient conditions for full 21st century skill development a nuance that distinguishes this study's findings from studies that treat technology adoption as uniformly transformative of student competencies.

The digital literacy gains documented in this study reflect a mode of technology engagement that goes beyond instrumental use. Students in this context were not merely operating devices; they were navigating information systems, interpreting database outputs, and evaluating the reliability of digital data competencies that Panduwinata and Setiawati (2024) identify as constitutive of higher-order digital literacy. This finding is practically significant: it suggests that embedding digital tools within authentic laboratory tasks, rather than teaching digital skills in isolation, produces more ecologically valid and transferable competencies. This insight has direct implications for curriculum design, particularly for madrasah science curricula that have traditionally separated technology instruction from laboratory practice.

The results of this study strengthen the view that science laboratories have a strategic function in the development of 21st century skills. Laboratories are not only a place to conduct scientific experiments, but also a learning medium that is able to integrate technology, communication, and problem-solving skills (Lestari & Malik, 2024). Therefore, the development of Smart Laboratory Management is an important step in supporting the transformation of modern science learning. Lestari and Malik's (2024) framing of the laboratory as an integrative learning medium is confirmed here, but the present study adds a governance dimension that their work did not examine: the laboratory's integrative function is





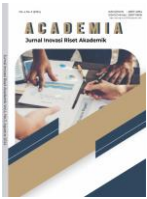
contingent upon administrative order. When inventory is mismanaged tools unavailable, materials expired, records inaccurate the laboratory's potential as a skill-development space is structurally undermined regardless of pedagogical intent. Smart Laboratory Management therefore functions as an enabling infrastructure for the laboratory's pedagogical mission, not merely as an administrative convenience.

Although the implementation of Smart Laboratory Management provides many benefits, this study also found several obstacles in its implementation. The main obstacles found are the limitations of laboratory technology infrastructure, such as the lack of computer devices, barcode scanners, and a stable internet network. This condition causes the implementation of the digital system to not run optimally in all laboratory activities. This infrastructure gap is not merely a technical problem but reflects a structural inequity in the distribution of educational resources. Madrasah and rural secondary schools in Indonesia disproportionately bear this constraint, raising an equity concern that technology-optimistic frameworks of laboratory digitalization tend to undertheorize. The implication is that policy interventions such as targeted government grants for laboratory digitalization in underserved schools are a prerequisite, not an afterthought, for the equitable scaling of Smart Laboratory Management.

In addition to infrastructure factors, the digital competence of laboratory personnel is also a challenge in the implementation of Smart Laboratory Management. Some science laboratories and teachers still need training related to the use of digital laboratory applications and the management of technology-based inventory systems. Low technological capabilities can hinder the effectiveness of using digital systems in laboratories (Modestus La'a & Vip Pramarta, 2023). This finding resonates with de-Torres et al.'s (2024) analysis of teacher digital competence assessment, which found that educators demonstrate sufficient skills for basic device operation but consistently underperform on system integration and data interpretation tasks precisely the competencies most demanded by Smart Laboratory Management applications. The practical implication is that generic "technology training" programs are insufficient; training must be context-specific, focusing on the laboratory management systems actually deployed in each school, and must be delivered through sustained professional development rather than one-off workshops.

Another obstacle is the limited budget for the development of digital technology-based laboratories. Procurement of technology devices, application development, and system maintenance require relatively large costs. Therefore, policy support and commitment from schools and the government are needed in supporting the transformation of digital laboratories. A cost-benefit analysis perspective, however, suggests that the initial investment in digital laboratory infrastructure is offset by long-term reductions in equipment loss, practicum cancellations, and administrative labor costs that manual systems silently generate but rarely quantify. Future research should attempt to measure these offset costs empirically, as a documented cost-benefit ratio would constitute a stronger evidence base for budget advocacy at the institutional and government-policy level.

Taken together, the obstacles identified in this study reveal that the challenges of Smart Laboratory Management implementation are systemic, not merely technical. They arise from the intersection of resource scarcity, capacity deficits, and institutional inertia a triad that cannot be addressed by technology adoption alone. This systemic character implies that school-level interventions (e.g., continuous professional development, infrastructure procurement) must be accompanied by enabling policy frameworks at the district and national level, including dedicated budget lines for digital laboratory infrastructure in the national education funding



formula, and competency standards for laboratory digitalization integrated into teacher certification programs.

The theoretical implication of this study is twofold. First, it positions Smart Laboratory Management as a sociotechnical construct rather than a purely technical one, requiring analysis at the intersection of organizational governance, pedagogical design, and digital infrastructure. Second, it extends the Society 5.0 education framework into the secondary and madrasah context, demonstrating that human-centered technology integration is both feasible and educationally productive at this level. Practically, school leaders and policymakers should reconceptualize laboratory management not as an administrative function separate from instruction, but as an integral dimension of instructional quality one that, when digitalized effectively, serves as a catalyst for 21st century skill development among students. The present study thereby contributes a contextualized, analytically grounded model of Smart Laboratory Management that future research can operationalize, test, and refine across diverse educational settings.

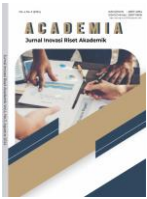
CONCLUSION

The implementation of Smart Laboratory Management based on digital technology has proven to improve the effectiveness, efficiency, and transparency of science laboratory management in supporting 21st-century science learning. The integration of digital inventory systems, barcode technology, laboratory management applications, and digital learning media not only simplifies administrative processes and accelerates access to laboratory information, but also strengthens the quality of practicum-based learning. The findings indicate that the transformation of laboratory management from manual systems into integrated digital systems contributes to more organized, accountable, and adaptive laboratory governance.

In the context of learning, Smart Laboratory Management supports the development of students' 21st-century skills, particularly digital literacy, collaboration, communication, creativity, and critical thinking. The integration of technology into practicum activities encourages students to become more active in scientific inquiry, data analysis, and collaborative problem-solving. Thus, digital-based laboratory management functions not merely as an administrative innovation, but also as a pedagogical infrastructure that supports student-centered science learning.

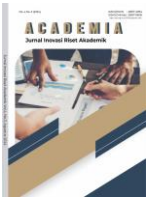
However, the implementation process still faces several challenges, including limited technological infrastructure, unequal digital competence among laboratory personnel, unstable internet access, and limited funding for system development and maintenance. These challenges indicate that the successful implementation of Smart Laboratory Management requires not only technological adoption, but also institutional readiness, sustainable professional development, and policy support.

Therefore, schools, madrasahs, and educational policymakers need to strengthen digital infrastructure, improve the digital competence of laboratory personnel and teachers, and provide sustainable support for laboratory digitalization programs. This study contributes theoretically by positioning Smart Laboratory Management as a sociotechnical system that integrates educational governance, digital technology, and 21st-century learning. Practically, the findings may serve as a reference for developing modern laboratory management systems that are more effective, adaptive, and relevant to the demands of future science education.



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