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Integrating Big Data and IoT in Physics Laboratory Information Systems: A Systematic Literature Review

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Abstract

Physics laboratories generate large volumes of complex experimental data that require efficient and secure management systems. The integration of Big Data and IoT offers solutions through real-time monitoring, automation, and advanced analytics. However, adoption in educational and small-scale laboratories remains limited due to high costs, data security issues, and technical skill gaps. This study employs a Systematic Literature Review (SLR) method, analyzing 30 articles published between 2017 and 2024 from open-access sources such as Google Scholar and IEEE Xplore. Data extraction focuses on applications, challenges, and synergies of Big Data and IoT in physics laboratory information systems. The findings highlight key applications such as real-time environmental monitoring, automated data collection, RFID-based inventory management, and advanced data analytics. The main challenges identified include high implementation costs, system incompatibility, and a lack of skilled personnel. The synergy between IoT and Big Data enhances accuracy, operational efficiency, and decision-making. This study presents a structured framework of challenges and corresponding solutions, and also highlights underutilized practices such as LIMS integration and adaptive environmental control. The contributions include theoretical insights into the digital transformation of laboratories and practical strategies based on CERN's case study that are applicable to educational and research labs.

Keywords: Automation; Big Data; Data Security; Information System; IoT; Physics Laboratory.

Abstrak

Laboratorium fisika menghasilkan data eksperimen kompleks dalam jumlah besar, yang membutuhkan sistem pengelolaan efisien dan aman. Integrasi Big Data dan IoT menawarkan solusi melalui pemantauan waktu nyata, otomatisasi, dan analitik canggih. Namun, adopsi teknologi ini di laboratorium pendidikan dan skala kecil masih terbatas karena biaya tinggi, isu keamanan data, dan keterbatasan keterampilan teknis. Penelitian ini menggunakan metode Tinjauan Sistematis Literatur (SLR) terhadap 30 artikel terpublikasi antara 2017–2024 dari sumber terbuka seperti Google Scholar dan IEEE Xplore. Fokus ekstraksi data mencakup aplikasi, tantangan, dan sinergi Big Data dan IoT dalam sistem informasi laboratorium fisika. Hasil menunjukkan penerapan utama berupa pemantauan lingkungan real-time, pengumpulan data otomatis, manajemen inventaris berbasis RFID, dan analitik data tingkat lanjut. Tantangan utama adalah biaya, ketidaksesuaian sistem, dan kekurangan tenaga ahli. Sinergi IoT dan Big Data meningkatkan akurasi, efisiensi, dan pengambilan keputusan. Studi ini menyajikan kerangka tantangan dan solusi, serta menyoroti praktik yang kurang dimanfaatkan seperti integrasi LIMS dan kontrol lingkungan adaptif. Kontribusi mencakup pemahaman transformasi digital laboratorium dan strategi praktis berbasis studi kasus CERN yang relevan bagi laboratorium pendidikan dan riset.

Kata kunci: *Big Data; IoT; Keamanan Data; Laboratorium Fisika; Sistem Informasi; Otomatisasi.*

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INTRODUCTION

Information technology has dramatically transformed the way data is collected, stored, and utilized across various fields, including physics laboratories. The emergence of Big Data and the implementation of the Internet of Things (IoT) have shown significant potential to enhance operational efficiency, facilitate data- driven decision-making, and optimize resource utilization in laboratory environments (Dinesh & Smith, 2024).

Physics laboratories, typically generate vast and complex datasets through experiments involving particle detection, optical sensors, and computational simulations. However, many laboratories still rely on traditional data management systems that are prone to inefficiencies, data inconsistency, and human error. The integration of Big Data and IoT offers a promising solution through real-time environmental monitoring, rapid analysis, and automation. Nevertheless, adoption remains limited due to high infrastructure costs, security concerns, and a lack of technical expertise among staff.

This study addresses the gap by conducting a Systematic Literature Review (SLR) to examine how Big Data and IoT technologies are applied in physics laboratory information systems. It aims to explore their practical implementations, associated challenges, and the synergistic effects of integrating both technologies. Specifically, this review is guided by the following Research Questions (RQs):

1. What are the main applications of Big Data and IoT in physics laboratory information systems?
2. What are the key challenges in implementing these technologies in laboratories?
3. How can their synergy improve operational efficiency and data accuracy?

Theoretically, this study contributes to the literature by mapping the current state of Big Data and IoT adoption in laboratory contexts and identifying underexplored areas. Practically, it provides evidence-based recommendations for stakeholders, including stepwise implementation strategies and best practices derived from successful models such as the CERN case study. These insights are particularly relevant for small-scale or educational laboratories aiming to transition toward digital transformation.

METHODS

The current study applies a Systematic Literature Review (SLR) process, adapted from Kitchenham et al. (2007), to search systematically, review, and examine Literature on integrating Big Data and IoT into physics laboratory information systems. Application of SLR ensures a systematic, transparent, and reproducible process, categorized into three phases: planning, conducting, and reporting the review[1].

Review Planning

The planning phase defined the scope and objectives of the review, focusing on the application of Big Data and IoT in physics laboratories to enhance operational efficiency and data accuracy. The following research questions (RQs) were formulated to guide the review:

- **RQ1**: What are the key applications of Big Data and IoT in physics laboratory information systems?
- **RQ2**: What are the primary challenges in implementing Big Data and IoT in physics laboratories?
- **RQ3**: How do Big Data and IoT synergize to improve operational efficiency and data accuracy in physics laboratories?

Five academic databases were selected for their relevance to physics, computer science, and technology: Google Scholar, ScienceDirect, Web of Science, IEEE Xplore, and MDPI. These databases were chosen to ensure comprehensive coverage of peer-reviewed journals, conference proceedings,

[1] The protocol for this systematic literature review was not registered in any public repository.

and open-access Literature. The review targeted articles published between 2018 and 2025 to capture recent advancements in Big Data and IoT technologies.

Inclusion and Exclusion Criteria

To ensure relevance and quality, the following inclusion and exclusion criteria were established: **Inclusion Criteria (IC)**:

- **IC1**: Articles must discuss the application of Big Data and or IoT in laboratory settings, with a preference for physics laboratories.
- **IC2**: Articles must be published in peer-reviewed journals, conference proceedings, or reputable preprint repositories.
- **IC3**: Articles must be written in English or Indonesian to include relevant local studies, particularly those addressing Big Data and IoT applications in physics laboratories within Indonesia.
- **IC4**: Articles must provide empirical evidence, case studies, or practical implementation frameworks.

Exclusion Criteria (EC):

- **EC1**: Articles that do not address Big Data or IoT in the context of laboratory management or physics experiments.
- **EC2**: Articles lacking methodological rigor or published in non-peer-reviewed sources.
- **EC3**: Articles written in languages other than English or Indonesian.
- **EC4**: Articles that are purely theoretical without practical applications or empirical data.

Search Process

A search string was developed to retrieve relevant articles "Big Data" OR "big-data" OR "data analytics" AND "Internet of Things" OR "IoT" OR "sensor networks" AND "physics laboratory" OR "laboratory information system" OR "LIMS" OR "laboratory management".

The search was conducted in April 2025, with filters applied to limit results to full-text articles published between 2018 and 2025. The initial search yielded 983 records (Google Scholar: 737, ScienceDirect: 108, Web of Science: 73, IEEE Xplore: 62, MDPI: 5). An additional 666 records were removed before screening: 23 duplicates, 232 marked as ineligible by automation tools (e.g., due to irrelevant fields or non-journal articles), and 411 excluded for other reasons (e.g., non-peer-reviewed sources, articles outside 2018–2025, or written in languages other than English or Indonesian). This left 572 records for screening.

Review Process

The article selection followed a multi-stage process, visualized using the PRISMA framework. In the first stage, the titles and abstracts of 572 records were screened against the inclusion and exclusion criteria, excluding 376 records primarily due to irrelevant topics or non-physics contexts. In the second stage, 196 reports were sought for retrieval to access their full texts. Of these, 68 reports could not be retrieved (e.g., due to restricted access or unavailability). The remaining 128 reports underwent full-text review for eligibility, with 98 reports excluded for the following reasons: methodology not aligned with inclusion criteria (n=39), irrelevant research context (n=23), and poor research quality (n=31). Ultimately, 30 studies were included in the qualitative synthesis, including a small number of Indonesian-language studies that met the inclusion criteria and were translated for analysis.

Data Extraction and Synthesis

Data from the 30 included studies were extracted using a standardized template, capturing details such as study objectives, methodologies, applications of Big Data and IoT (e.g., real-time monitoring, data analysis, automation, inventory management), implementation challenges (e.g., infrastructure costs, data security, system compatibility), and key findings (e.g., synergies improving efficiency and accuracy). Themes were developed inductively, with the interpretation and coding process conducted collaboratively through discussion. Mendeley was used as the reference management software. For Indonesian-language studies, key sections were translated into English to facilitate synthesis. The extracted data were synthesized through thematic analysis to identify key trends, challenges, and synergies, addressing the research questions. They were summarized where available. Qualitative insights were categorized to provide actionable recommendations for physics laboratory practitioners in educational and research laboratories worldwide.

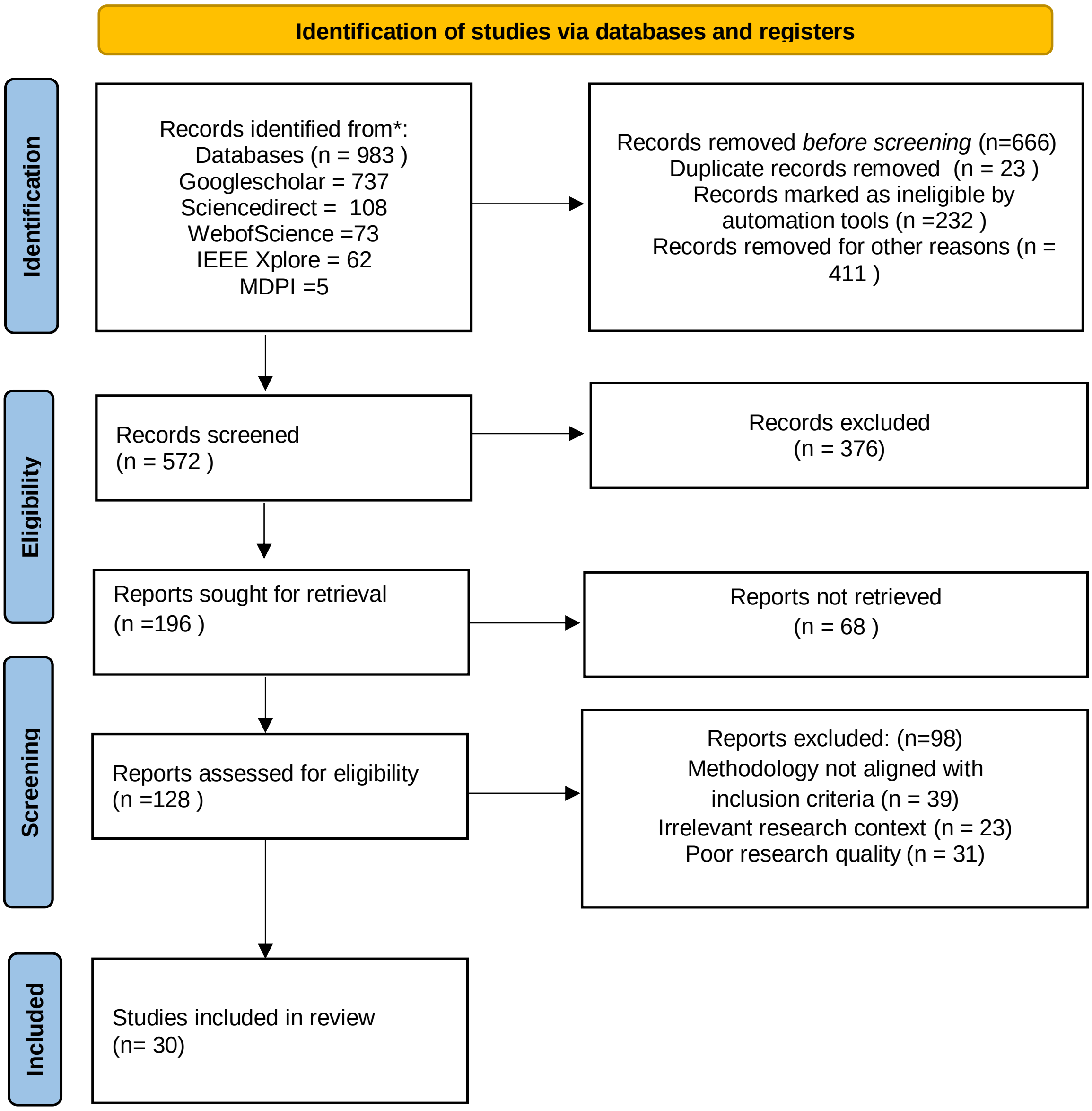

Figure 1. PRISMA Flow Diagram for Study Selection

RESULTS

KEY TRENDS IN THE APPLICATION OF BIG DATA AND IOT IN PHYSICS LABORATORIES

The review results indicate that the integration of Big Data and IoT technologies in physics laboratories has led to four main trends in the implementation of laboratory information systems.

1. **Real-Time environment monitoring using IoT Sensors**

   The application of Big Data and the IoT to a laboratory information system can enhance the precision and operational efficiency of the data. Using sensors for real-time monitoring is indispensable. Within the premises of physics labs, IoT sensors are utilized to monitor temperature, pressure, humidity, as well as magnetic fields (Dinesh & Smith, 2024). Real-time monitoring can ensure stable experimental conditions, which is especially important for high-precision physics experiments such as quantum mechanics simulations and vacuum tests. Nonetheless, technical challenges, such as the integration of data into Big Data platforms, are obstacles that must be overcome to ensure the reliability of these systems.

2. **Big Data platforms for experimental data analysis**

   Big Data is increasingly used to manage and analyze large-scale physics experiment datasets (particularly in spectroscopy, quantum simulation, and fluid dynamics). Platforms like Apache Spark enable faster data processing than traditional statistical methods and improve anomaly detection (Tian et al., 2019; Devineni et al., 2023). Nevertheless, successful adoption is limited by IT infrastructure constraints, high costs, and data privacy (Gkrimpizi et al., 2023). Additionally, the integration of Big Data with the IoT for the automation of laboratory devices is also an important trend in the literature.

3. **Laboratory Equipment Automation**

   The integration of IoT into laboratory equipment, such as oscilloscopes, particle detectors, and spectrometers, significantly reduces manual workload and minimizes human error during data collection (Kostadimas et al., 2025; Fawzy & Moussa, 2022). Automated enables seamless data capture and synchronization with cloud databases, facilitating deeper data analysis and potentially leading to new research methodologies. This integration represents a major trend in the literature on laboratory device automation (Jain et al., 2025). However, successful adoption requires addressing IT infrastructure limitations, high costs, and data privacy concerns (Gkrimpizi et al., 2023).

4. **IoT in Inventory Management**

   The positive impact of IoT technology on laboratory inventory management is very promising. The RFID tags (radiofrequency identification device) have a role to play since it possible to trace laboratory equipment such as measuring instruments, chemicals, and experimental devices. Efficient inventory utilisation can reduce the chances of inventory loss and damage, apart from facilitating optimum utilisation of the laboratory (Unhelkar et al., 2022). These systems also facilitate researchers in locating the existence of inventory and planning future experiments without disrupting logistics. However, the security of RFID data, the expense of attaching RFID tags, and the interface of information systems are problem (Adenekan, 2022).

Table 1. Applications, Benefits, and Challenges of Big Data and IoT in Physics Laboratories

Aspects	Technology	Application	Benefits	Challenges
Real-Time Environmental Monitoring	IoT Sensors	Monitoring temperature, pressure, humidity, and magnetic fields	Reduces data inconsistency	Sensor calibration, data integration, high initial costs

Experimental Data Analysis	Big Data Platforms	Analysis of spectroscopy, quantum simulations, and fluid dynamics data	Increases analysis speed	Robust IT infrastructure, high costs, and data security risks
Laboratory Equipment Automation	IoT and Cloud	Integration with oscilloscopes, spectrometers, and particle detectors	Reduces manual processing time	Significant initial investment, staff training, and device compatibility
Inventory Management	RFID and IoT	Tracking chemicals, measuring instruments, and laboratory devices	Improves efficiency and reduces inventory loss	Data security, RFID implementation costs, and system integration

Overall, the combination of Big Data and IoT offers the promise of more intelligent operation and optimized productivity but can also enhance the lattor's capability to generate consistent and reliable data (Elias et al., 2020). However, technical complexity, high cost, data security, and HR training requirements remain important issues to overcome. For laboratories looking to use this technology, we recommend starting with implementing IoT sensors for real-time environmental monitoring before moving on to Big Data. This step enables Physics laboratories to fully utilize the potential of Big Data and IoT to improve data accuracy and operational efficiency (Morchid et al., 2024).

DISCUSSION

PRACTICAL IMPLICATIONS AND SYSTEM INTEGRATION

The integration of Big Data and IoT in physics laboratories enables significant improvements in data accuracy, efficiency, and automation. Wireless sensor networks facilitate real-time monitoring of environmental parameters such as temperature, humidity, and pressure (Harb et al., 2017a), reducing manual errors and enhancing data reliability. Furthermore, this integration supports complex data analysis, enabling predictive modeling and improved decision-making processes (Kalburgi, 2024; Patrício et al., 2025).

LABORATORY INFORMATION MANAGEMENT SYSTEM (LIMS)

The software known as Laboratory Information Management System (LIMS) is designed to manage and integrate various types of data and information generated in the laboratory (Boyar et al., 2021). LIMS offers a platform capable of handling various data management processes, such as collection, recording, storage, and maintenance of related information (Oluwole et al., 2022). Additionally, LIMS assists in the precise processing, retrieval, and validation of data, ensuring that the data used in various analyses and research is accurate. Web-based LIMS can enhance laboratory management efficiency.

By implementing this system, laboratories can optimize resource management, improve record accuracy, and accelerate the decision-making process based on well-organized data (Oluwole et al., 2022). This system makes laboratory data recording easier and more organized. Additionally, web-based integration accelerates reporting, analysis, and decision-making as it allows users to access information directly from various locations. Furthermore, this accessibility improves operational transparency, minimizes the risk of data loss or errors, and supports laboratory management in optimizing resource allocation and enhancing overall productivity (Ahsun & Elly, 2024).

THE ROLE OF BIG DATA AND IOT IN LIMS

Processing large and complex experimental data is a major challenge in physics laboratories, both at the educational and basic research levels. Although the scale of the data smaller than modern physics experiments such as those at CERN, classical experiments such as gravitational acceleration measurements, light spectrum analysis, or thermodynamic studies still generate large, multidimensional datasets. These information incorporate factors such as time, position, speed, temperature or weight, and come from different sources such as IoT sensors or robotized estimation gadgets (Di Meglio et al., 2023).

The use of Big Data in physics laboratories provides significant benefits, including data integration from multiple sources, distributed data storage, fast analysis, and system scalability. For example, in a perfect gas experiment, temperature and pressure data were processed in real-time using Spark to generate graphs showing the linear relationship between the two variables (Li, M., et al. 2022). In addition, Big Data systems can be scaled to handle increasing data volumes without major changes to existing infrastructure, such as when mechanical experiments generate more data due to an increased number of sensors (Jarašūnienė et al., 2023).

The application of IoT in LIMS enables real-time monitoring of environmental parameters such as temperature, humidity, air pressure, and air quality. This is crucial for maintaining the performance of equipment and the precision of experimental results. IoT sensors collect information coordinates with the LIMS , giving real-time dashboards, programmed notices, and planned reports. In expansion, IoT bolsters the mechanization of natural controls, such as HVAC settings or shrewd fridges. The main benefits of IoT implementation include improving the accuracy of experimental results, preventing equipment damage and material degradation(Dinesh & Smith, 2024) .Making strides operational proficiency and research facility security (Samonte et al., 2021). Cases of IoT applications incorporate observing delicate chemical capacity, thermodynamic tests, cleanrooms, and instructive research facilities (Islam et al., 2024).Be that as it may, challenges such as foundation costs, information security, framework compatibility, and preparing needs ought to be tended to (Alshar'e, 2023).

CHALLENGES AND SOLUTIONS FOR IOT AND BIG DATA IMPLEMENTATION IN LABORATORIES

Table 2. Challenges and solution for IoT and Big data

Challenges	Description	Proposed Solutions	References
High Implementation costs	Setting up IoT devices,servers, and cloud systems requires large investments, especially for scaling.	ROI-based evaluation and selection of cost-effective,scalable, and infrastructure compatible technologies	(Gregorcic & Linder, 2022); (Goundar et al., 2021)
Data security threats	Threats like malware,hacking, and sensitive data leaks can affect privacy and institutional reputation.	Implementation of encryption, two-factor authentication, and AI supported real-time monitoring systems.	(Said et al., 2024) ; (Ahmad et al., 2021); (Herlina, et al.2023).
Skill gaps among laboratory staff	Staff often lack the technical skills to manage IoT devices and perform data analytics effectively.	Conduct comprehensive training on IoT and Big Data tools, focusing on analytical and integration competencies.	(Malar, G et al. 2025).
System Integration and compatibility	Incompatibility between IoT, Big Data systems, and LIMS can hinder integration and workflow	Choose devices and platforms that support interoperability and can integrate smoothly with existing systems.	(Alshar'e, 2023)

Evidence shows that the use of IoT and Big Data technologies at the same time significantly improves the quality of information in physics laboratories. This can be seen through live data collection, editorial analysis and decision-making processes. IoT sensors make it possible to monitor real-time data from laboratory environmental conditions, including temperature, pressure and humidity, and send online to Big Data platforms for analysis (Munir et al., 2022). This combination reduces the probability of data consistency which ensures the stability of experimental conditions. In addition, the Big Data platform uses algorithms to increase the speed of data analysis, but also increases the accuracy of predicting experimental results. The use of RFID tags integrated with the IoT system also supports the direct management of laboratory inventory, thereby improving the efficiency of inventory management (Muchsin et al., 2024) With the deep insights generated from real-time and historical data, laboratories can make strategic decisions for future experiment planning, resource usage optimization, and budget allocation (Harb et al., 2017b). Thus, the combination of IoT sensors for live monitoring and Big Data for experimental data analysis creates a more efficient, accurate, and reliable laboratory.

Relevance of the CERN Case Study

The CERN example offers valuable lessons to be used in education or laboratory of modest size. First, the WLCG global data sharing principle (Di Meglio et al., 2023), can be applied to classical experiments, for example, by exploiting cloud storage. This enables scientists to work together even if they are in separate places. Second, to reduce the cost of operation, general experiment site can make use of the automatic control systems that are used to calibrate equipment and provide decision support for the predict maintenance system (Goundar et al., 2021). Where heating temperature can be actively monitored, and alarm will be triggered once the temperature exceeds a set point (Shen et al., 2018). In the field of the physics laboratory, the Big Data and IoT have great activities. Such technology improves the efficiency and accuracy of research, and facilitates cooperation of numerous researchers, and assists in managing of large and complicated data. Yet the deployment of this technology is not without its challenges, including latency of communication, securing data and an established infrastructure (Said et al., 2024). In order to solve these problems, both cybersecurity protocols and grid computing are some of the remedies that CERN has adopted (Di Meglio et al., 2023).

CLOSING

This systematic literature review identifies the key applications, challenges, and synergies involved in integrating Big Data and IoT within physics laboratory information systems. The review addresses the following research questions

(RQ1): The primary applications of these technologies include real-time environmental monitoring, automated data collection, inventory management, and enhanced analytical capabilities.

(RQ2): The main challenges are high implementation costs, data security concerns, system integration difficulties, and a lack of technical expertise.

(RQ3): The synergy between Big Data and IoT facilitates more accurate data acquisition, faster analysis, and more informed decision-making, thereby enhancing overall laboratory efficiency.

This review presents a novel synthesis by organizing the challenges and solutions into a structured framework, drawing insights from 65 studies. It highlights underutilized applications such as real-time environmental control and inventory automation through RFID and LIMS integration. Furthermore, the review draws practical insights from the CERN case study to propose scalable strategies suitable for educational and small-scale laboratories.

Theoretically, this study contributes to the literature by mapping the digital transformation of laboratory environments and emphasizing the role of data synergy in enhancing operational efficiency. It also reinforces the increasing intersection between information systems and experimental physics.

However, this study has certain limitations. First, it includes only English-language publications and those accessible through open databases. Second, although data extraction was discussed collaboratively, no formal inter-rater reliability test (e.g., Cohen's Kappa) was conducted, which may introduce selection bias.

Future research should focus on the empirical validation of the proposed strategies, including pilot implementations of IoT–Big Data integration in small-scale or educational laboratories. It is also recommended to explore domain-specific LIMS customization and evaluate their impact on laboratory performance through experimental or case study approaches.

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