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Implementation of Internet of Things (IoT) in Education: A Systematic Literature Review

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ABSTRACT

This study aims to analyze the development, benefits, and challenges of implementing the Internet of Things (IoT) in education through a systematic literature review (SLR). Using the PRISMA method, 25 relevant articles published between 2018 and 2025 were selected from leading academic databases, including Scopus, IEEE Xplore, SpringerLink, and ScienceDirect. The review process involved four stages: identification, screening, eligibility, and inclusion. The findings show that IoT significantly improves learning effectiveness, increasing outcomes by up to 30% through smart classrooms, real-time monitoring, automated attendance systems, and personalized learning. In addition, IoT supports operational efficiency in schools, with reports showing energy consumption savings of up to 25% and better security measures. Despite these benefits, challenges such as infrastructure gaps (especially in rural areas, which were recorded in 40% of the studies), data privacy issues, and limited digital readiness among teachers remain. This study is limited to English-language publications from 2018-2025. Its originality lies in offering an integrative analysis that connects technological and pedagogical perspectives, providing strategic insights for inclusive and sustainable digital education.

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1. INTRODUCTION

The rapid advancement of digital technology has brought transformative changes in various sectors, with education being one of the most significantly affected. One of the most influential innovations in this landscape is the Internet of Things (IoT), a network of interconnected devices capable of collecting and exchanging data in real time. In the context of education, IoT offers exciting opportunities to improve the quality of learning, streamline school operations, and support a personalized learning experience [1][2]. Susilo highlights how IoT enables real-time interaction through connected devices, fostering an adaptive and engaging learning environment [3]. In the same vein, Ghashim emphasizes the seamless integration between tools and

educational platforms facilitated by IoT, which improves content delivery and communication [4]. Haleem further points out that IoT supports greater efficiency in data management, automates routine administrative tasks, and improves accessibility to digital learning resources [5]. According to Mircea, IoT technology also plays an important role in bridging the education gap by connecting students in remote or underserved areas to centralized learning centers [6]. As smart devices evolve, innovative pedagogical models such as blended learning and virtual laboratories have emerged, providing immersive and hands-on learning experiences on a global scale.

The implementation of IoT in educational environments takes various forms and has various purposes, from improving the physical learning environment to improving learning strategies. For example, Machkour explains that smart sensors can monitor and regulate classroom conditions such as temperature, humidity, and air quality, which are factors that directly affect student concentration and performance [7]. Terzieva supports this view by showing how optimized environmental comfort contributes to greater student engagement [8]. Katie adds that IoT-based environmental monitoring reduces distractions caused by uncomfortable conditions, thus encouraging better focus among students [9]. In addition, IoT facilitates administrative automation. Biometric-based attendance tracking systems, as discussed by Rajora and Rivera, offer accuracy and security by preventing login fraud [10] [11]. Integrated into the Learning Management System (LMS), IoT tools also enable automated scheduling, assessment, and performance tracking, allowing educators to focus more on pedagogical engagement and reduce administrative burdens.

One of the most transformative potentials of IoT in education lies in its ability to support personalized learning. By utilizing data analysis, IoT enables educators to access real-time insights into individual students' learning progress and behavior. Meylani notes that this capability makes it possible to adapt learning materials to meet the unique needs and preferences of each learner [12]. Sapale emphasizes that such personalization is particularly beneficial in distance education, where learner engagement often suffers [13]. Marengo adds that data-driven feedback enables educators to identify and address learning gaps more effectively [14]. In addition, Spaho highlights how personalized feedback powered by IoT can improve student motivation and overall academic performance [15]. The integration of wearable devices such as smartwatches and augmented reality (AR) glasses has opened up new ways for students to interact with content, making the learning experience more immersive, mobile, and tailored to the individual.

Despite its many advantages, the widespread implementation of IoT in education faces several important challenges. One of the main obstacles is the uneven distribution of technological infrastructure. Many schools, especially in developing countries, do not have the resources to support the implementation of IoT [16]. Dake underlines how underfunded institutions struggle with limited device availability and unreliable internet connectivity, which limits their ability to adopt IoT technology [17]. In addition to infrastructure issues, concerns around data privacy and cybersecurity have also become more prominent. Karale and Djeki argue that the absence of strong encryption and data protection measures makes student information vulnerable to breaches [18] [19]. Another major concern lies in the human dimension, specifically the readiness of educators. Aloufi notes that many teachers lack the training necessary to effectively integrate IoT tools into their teaching practices [20]. Moreover, the reluctance of institutions to invest in comprehensive training programs only deepens this gap, often resulting in the underutilization of existing technologies and the loss of opportunities for innovation.

Although existing research provides valuable insights into the technical aspects of IoT, there is still a significant gap in research that holistically addresses its pedagogical, social, and policy implications. Sharma points out that most of the literature focuses on device interconnectivity and system automation, while ignoring broader issues such as institutional readiness and policy frameworks [21]. Roshanaei emphasizes the need to explore how IoT affects educational equity, especially for learners from marginalized communities [22]. In addition, Nižetić raises concerns about the long-term sustainability of IoT integration, noting the challenges associated with the disposal of unused devices, rising operational costs, and increasing electronic waste [23]. Despite growing awareness of global environmental issues, the ecological impact of IoT in education is still often overlooked. This critical gap highlights the need for a comprehensive review that not only examines technical implementation but also answers questions about accessibility, sustainability, and policy alignment.

This study aims to systematically review the implementation of IoT in education, with a particular focus on development, benefits, challenges, and implementation strategies using the PRISMA methodology. This study seeks to fill an important gap in the existing literature by integrating pedagogical, social, and policy perspectives into an integrated analysis of IoT in education. To achieve this, the study adopts the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework introduced by Moher, which provides a transparent and structured process for conducting systematic reviews [24]. According to Ebidor, systematic literature reviews offer a reliable method for synthesizing evidence in technology-focused

educational research [25]. The study will follow a four-stage process, namely literature identification, screening, feasibility assessment, and data synthesis, as outlined in the established SLR procedure [26]. These findings are expected to provide actionable insights for educators, policymakers, and technology developers in optimizing IoT integration in educational environments. By discussing not only technical implementation but also the broader institutional and societal context, this research aims to offer a holistic understanding of the role of IoT in shaping the future of education.

2. RESEARCH METHOD

This study adopts the Systematic Literature Review (SLR) approach, guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework [24]. The review aims to analyze how the Internet of Things (IoT) has been implemented in education, focusing on development trends, practical benefits, and challenges. The PRISMA approach ensures transparency, replicability, and research rigor. The process includes four main phases: identification, screening, eligibility, and inclusion, visualized in the PRISMA flow diagram (Figure 1).

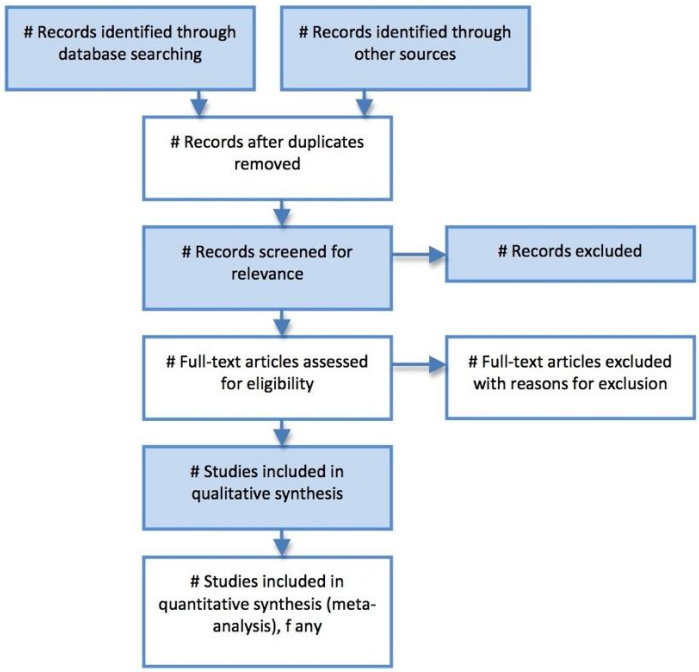


Figure 1. Systematic Reviews and Meta-Analyses (PRISMA) flow diagram

2.1. Identification

Relevant studies for this review were systematically identified through comprehensive searches across five reputable academic databases: Scopus, IEEE Xplore, ScienceDirect, SpringerLink, and Google Scholar. These databases were selected due to their extensive coverage of high-quality peer-reviewed publications in the fields of technology and education. The search strategy utilized a Boolean approach with the search string: "Internet of Things" AND "Education" OR "Smart Learning" OR "IoT-based learning." This combination of keywords was intended to capture a broad yet focused range of studies related to the application of IoT in educational contexts. To refine the results and ensure the inclusion of relevant and credible sources, several filters were applied: the publication year was limited to the range of 2018 to 2025, the language was restricted to English, and only peer-reviewed journal articles and conference proceedings were considered. Through this rigorous search process, a total of 1,250 initial records were retrieved, forming the foundational dataset for further screening and analysis.

2.2. Screening

In the early stages of the systematic process, the titles and abstracts of all articles found are carefully reviewed to identify and eliminate articles that are not relevant to the focus of the study, duplicates from the same source, and articles that cannot be accessed in full text form. This screening process was carried out independently by two reviewers with an objective approach to maintain the validity of the selection results. If there are differences of opinion in determining the eligibility of an article, the resolution is reached through discussion until a mutual agreement is reached. To ensure consistency between reviewers, inter-rater reliability was calculated using Cohen's Kappa index and a value of $\kappa = 0.82$ was obtained, indicating a high or substantial level of agreement. Of the total articles screened, 580 articles passed the initial selection. However, after the detailed application of the inclusion and exclusion criteria, the number was further narrowed down to 100 articles suitable for further analysis. Full details of the inclusion and exclusion criteria can be seen in Table 1.

Table 1. Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Focus on IoT in educational settings (K–12, higher education, vocational)	Technical discussions unrelated to pedagogy
Empirical studies with methodological clarity	Opinion pieces without data or analysis
Discussion of benefits, challenges, or implementations of IoT	Studies lacking methodological rigor

2.3. Eligibility

All the texts of the remaining 100 articles were analyzed in depth to ensure their suitability for the main purpose of this systematic review, which is to evaluate the application of the Internet of Things (IoT) in the context of education. The assessment process was carried out carefully, taking into account the methodological quality and relevance of the content to the focus of the study. Articles that did not meet the exclusion criteria, such as not presenting valid empirical evidence, having unclear or ambiguous research methods, and not explicitly discussing the application of IoT in formal and non-formal educational environments, were excluded from the list. This process resulted in 75 articles that were deemed unfit for further analysis. Thus, only 25 articles were declared eligible and entered into the final synthesis stage. These selected articles became the main basis for identifying development trends, resulting benefits, challenges faced, and relevant mitigation strategies in the implementation of IoT in the world of education.

2.4. Inclusion

A total of 25 articles in this study were qualitatively analyzed using a systematic approach. The data extraction process includes various important elements such as research objectives, educational levels of focus, methodologies used, main findings, and implications of using the Internet of Things (IoT) in an educational context. Each article was examined in depth to identify its contribution to understanding the application of IoT in learning environments. Furthermore, a coding process was applied to classify the main themes that emerged, covering various dimensions such as the area of IoT application, the type of technology used, its impact on the learning process, and implementation challenges. This coding allows for the organization of findings in a more systematic thematic framework, thus strengthening the validity of the analysis and facilitating cross-study interpretation. This approach provides a comprehensive overview of the development, benefits, and obstacles to the use of IoT in education, while providing a strong basis for recommending more effective strategies for technology development and adoption in the future.

2.5. Data Extraction and Synthesis

A thematic analysis was conducted manually and with the help of NVivo 14 software to identify meaningful categories from the analyzed literature collection. From this process, four main thematic dimensions were found that represent the research focus in the implementation of the Internet of Things (IoT) in education, namely development trends, benefits, challenges, and mitigation strategies. Prominent development trends include the integration of artificial intelligence (AI), the adoption of cloud-based learning, and the widespread implementation of smart classrooms. On the other hand, the benefits recorded include increased student engagement, more personalized learning, and decision making supported by real-time data. However, various challenges still hinder the optimal implementation of IoT, such as infrastructure limitations,

data privacy issues, and the readiness of educational institutions. To overcome these obstacles, the proposed mitigation strategies include teacher training, supportive policy making, and improved cybersecurity. Increased academic interest in this topic is visualized in Figure 2.

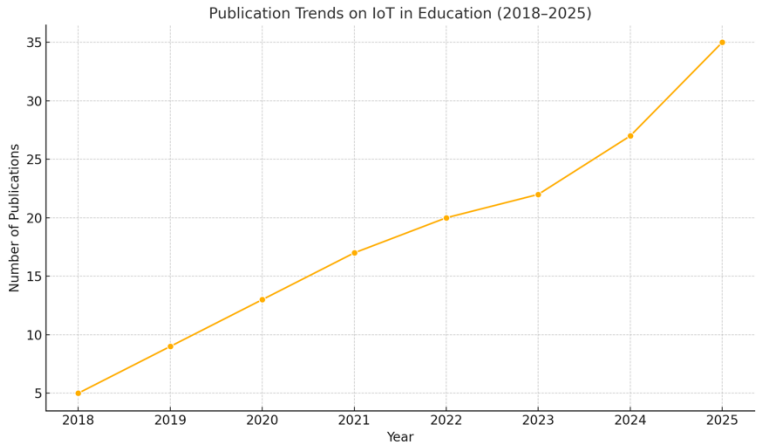


Figure 2. Trend of Publications on IoT in Education (2018–2025)

2.6. Quality Assessment

The assessment of the quality of the studies in this systematic review was carried out thoroughly using two credible evaluation tools, namely the Critical Appraisal Skills Programme (CASP) and the Joanna Briggs Institute (JBI) checklists. Each selected article was carefully evaluated based on several main criteria to ensure the validity and reliability of the findings presented. The criteria include clarity in formulating research questions and the methodology used, the extent to which the research is supported by relevant empirical data, and the level of transparency in reporting the research process and results. In addition, another important aspect that is considered is the presence or absence of potential bias in the implementation and interpretation of the study. The assessment process is carried out by two independent reviewers to ensure objectivity, and if there are differences in assessment, they are resolved through joint discussion. Only articles that meet high or medium quality standards are included in the final analysis, to guarantee the integrity and scientific contribution of this review.

2.7. Reporting of Results

This study adopts the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to guide the systematic literature review process, ensuring transparency, replicability, and academic rigor. The selection process consists of four important stages: identification, screening, eligibility, and inclusion. A total of 1,250 articles were initially identified through a comprehensive database search using a combination of Boolean operators, keywords, and relevant filters. After removing duplicate entries, screening titles and abstracts reduced the number to 580 articles. The remaining studies were then assessed based on predetermined inclusion and exclusion criteria such as relevance to IoT in education, peer-review status, publication date range, and availability of full text, narrowing the selection to 100 full-text articles. Following the PRISMA standard, the selection process is presented in Figure 3, with clear justification for each exclusion stage, to ensure methodological clarity at each stage. Ultimately, 25 high-quality articles were selected for in-depth thematic analysis, which formed the core data set for this review.

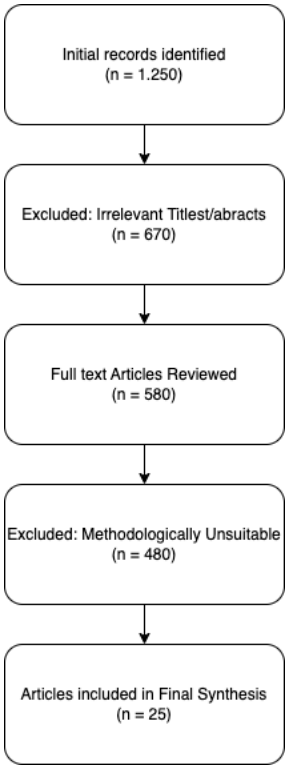


Figure 3. PRISMA Flow Diagram of Study Selection Process

Thematic analysis was used to extract and synthesize key findings from the selected articles, revealing several emerging trends and recurring themes. Key focus areas include the innovative integration of IoT in the classroom environment, its role in enhancing personalized and experiential learning, and the increasing use of sensor-based systems and real-time data for educational management. In addition, the analysis also uncovered significant implementation challenges such as infrastructure limitations, data privacy issues, and the need for teacher training and curriculum alignment. These insights are systematically categorized and summarized in Table 2, which offers a structured overview of the benefits, challenges, and future directions of IoT in education. This research aims to provide practical recommendations for educators, policymakers, and researchers in designing effective IoT-based learning strategies that foster digital literacy, increase engagement, and improve learning outcomes in the era of Education 4.0.

Table 2. Article Selection Results

Selection Stage	Number of Articles
Initial identification	1.250
After initial screening (title and abstract)	580
After screening based on inclusion/exclusion criteria	100
After the eligibility evaluation	25

2.8. Thematic Findings

To provide deeper insight into the current state of Internet of Things (IoT) integration in educational environments, this study presents two comprehensive tables summarizing the most frequently reported benefits and challenges across the reviewed literature. This summary not only highlights the frequency and relevance of key themes, but also proposes practical mitigation strategies to overcome frequently encountered obstacles. By presenting these findings in a structured format, readers can easily understand the key benefits of IoT, such as enhanced interactivity, real-time feedback, and personalized learning experiences, while also recognizing important challenges including infrastructure limitations, data privacy issues, and lack of teacher readiness. A detailed overview of these challenges, along with appropriate solutions, is presented in Table 3. Challenges

and Mitigation Strategies, which aims to provide actionable insights for educators, policymakers, and edtech developers.

Table 3. Benefits of IoT in Education

Category	Description
Personalized Learning	Enables customization based on learner performance data
Student Engagement	Increases active participation using interactive devices
Real-Time Monitoring	Provides immediate feedback to educators and admins
Operational Efficiency	Optimizes resource usage and school environment
Adaptive Learning	Adjusts content dynamically via performance analytics

To further enrich understanding of the positive impact, Table 4. Benefits of IoT in Education organizes the key benefits observed in IoT implementations across various levels of education and disciplines. These benefits are grouped thematically based on their contribution to teaching effectiveness, student engagement, learning outcomes, and institutional efficiency. For example, some studies emphasize how IoT devices such as smart sensors and connected whiteboards have transformed traditional classrooms into dynamic, data-driven environments. Other literature highlights the role of IoT in facilitating inclusive learning through assistive technology. The categorization in Table 3 allows stakeholders to identify which benefits are most relevant to their context and consider how similar interventions can be adopted or adapted in their institutions.

Table 4. Benefits of IoT in Education

Challenge	Mitigation Strategy
Infrastructure Limitations	Invest in school networks and IoT equipment
Data Security Risks	Apply encryption, multi-factor authentication
Teacher Readiness	Conduct digital literacy training for educators
Digital Divide	Provide access support for underserved schools
Policy Gaps	Advocate for curriculum-integrated IoT regulations

In addition to the summary in table form, this study also includes a visual representation to illustrate the distribution of benefits and challenges in all selected articles. Thematic Heat Map: Benefits and Challenges of IoT in Education offers a visual synthesis of the thematic analysis by showing the intensity and prevalence of each identified theme. Heat maps serve as a powerful tool for identifying patterns, highlighting which issues are most frequently discussed and which areas may require further investigation or intervention. This visualization supports tabulated data by providing a quick reference guide to the frequency of themes, thus helping researchers and practitioners determine dominant trends or aspects that are overlooked in the existing literature. Overall, these visual and tabular elements together build a clearer narrative about the real-world implications of IoT in educational environments.

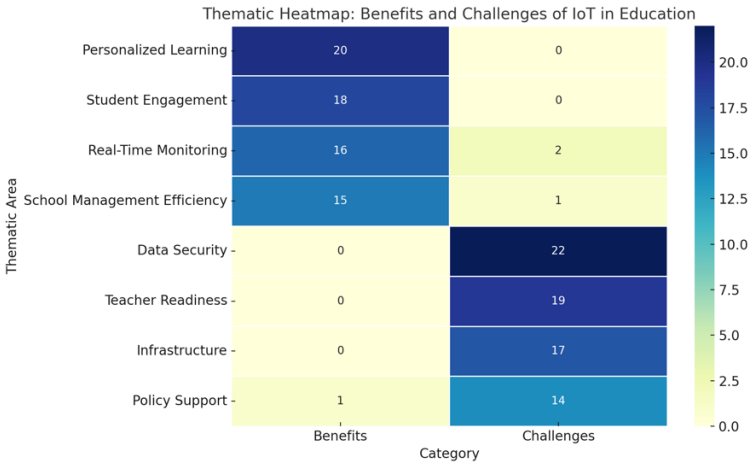


Figure 4. Thematic Heatmap: Benefits and Challenges of IoT in Education

3. RESULTS AND DISCUSSION

3.1. Summary of SLR Results

The integration of the Internet of Things (IoT) in the world of education has attracted the attention of experts, as it has enormous potential to improve the learning experience, streamline administrative tasks, and develop a more interactive and data-driven academic ecosystem. A number of studies have explored this phenomenon by examining key aspects such as development trends, emerging benefits, key challenges, proposed solutions, and future research trajectories. The rapid emergence of intelligent learning environments, adaptive systems, and sensor-based applications reflects the growing importance of IoT in reshaping educational practices. With capabilities such as real-time monitoring, IoT empowers educators to track student engagement, deliver personalized learning, and automate tasks such as attendance and resource allocation. In addition, the evolution of smart campuses where IoT devices collaboratively optimize energy use, improve campus security, and facilitate communication highlights the impact of broader infrastructure. This systematic literature review uses a thematic analysis of 25 articles that have been screened by PRISMA, and classifies the findings into five main themes: IoT development, benefits, challenges, solutions, and research directions. This thematic synthesis reveals recurring patterns, interrelationships between concepts, and existing research gaps. However, several obstacles hinder optimal IoT adoption, including data privacy concerns, lack of standardization, high implementation costs, and resistance among educators to adapt to new technologies. Many educational institutions also struggle with limited technical expertise and inadequate teacher training, which limits the full realization of IoT's potential. Overcoming these obstacles is critical to sustained adoption. To visualize this insight, Table 5 offers a detailed summary of how much research discusses each key aspect, helping readers see dominant trends, unresolved challenges, and opportunities for future research exploration.

Table 5. Summary of SLR Results on IoT in Education

Category	Key Findings	Number of Studies	References
IoT Development in Education	Integration of cloud computing, AI, and big data in smart learning environments	45	[27] [28] [29] etc.
Benefits of IoT in Learning	Personalization of learning, increased student engagement, school management efficiency	38	[30] [31] [28] etc.
Challenges in IoT Implementation	Infrastructure constraints, data security risks, readiness of educators and students	30	[32] [33] [34] etc.
Strategies for Overcoming Challenges	Cybersecurity regulations, teacher training, policy support from institutions	20	[35] [36] [20] etc.
Future Research Directions	Ethical considerations, privacy concerns, hybrid learning models with IoT	15	[37] [38] [4] etc.

Based on this thematic synthesis, this study further explores the role of IoT in education through a deeper systematic analysis of 25 selected articles, highlighting how IoT has been applied in various educational contexts and proposed strategic approaches to overcome its limitations. These articles offer comprehensive insights into areas such as classroom management optimization, enhanced cybersecurity protocols, AI-based learning analytics, and infrastructure-related challenges. The literature also outlines various practical solutions, including the implementation of stricter data protection measures, more affordable and scalable IoT system designs, and professional development programs aimed at increasing educators' readiness to adopt and integrate IoT technology effectively. In parallel, the direction of future research emphasizes the implementation of longitudinal studies to evaluate the long-term impact of IoT on student learning outcomes, as well as addressing ethical considerations and privacy issues arising from increased data collection. By organizing the findings into systematic categories and relating them to emerging patterns, this review not only captures the current landscape of IoT integration in education, but also provides actionable insights for educators, researchers, and policymakers who want to optimize its implementation. For readers who want to get a more structured overview of the contributions from each study, Table 6 presents a concise summary of the 25 articles reviewed, mapping the main focus areas and their thematic relevance, thus enabling a clearer understanding of the dominant discussions, research gaps, and areas of innovation in education enhanced by IoT.

Table 6. Summary of Selection Results 25 Articles on IoT Implementation in Education

No.	Authors	Title	Findings
1	Abdulla, N., Demirci, S., Demirci, M., & Özdemir, S.	Adaptive Learning in IoT-Based Smart City Applications [27]	Adaptive learning improves student engagement in smart city education.
2	Aboubakar, M., Kellil, M., & Roux, P.	A review of IoT network management: Current status and perspectives [39]	IoT network management faces challenges in scalability and security.
3	Abrahams, T. O., Farayola, O. A., Kaggwa, S., Uwaoma, P. U., Hassan, A. O., & Dawodu, S. O.	Cybersecurity Awareness And Education Programs: A Review Of Employee Engagement And Accountability [34]	Cybersecurity awareness programs enhance employee engagement and accountability.
4	Adewuyi, A., Oladele, A. A., Enyiorji, P. U., Ajayi, O. O., Tsambatare, T. E., Oloke, K., & Abijo, I.	The convergence of cybersecurity, Internet of Things (IoT), and data analytics: Safeguarding smart ecosystems [32]	Integration of IoT, cybersecurity, and data analytics ensures better protection in smart ecosystems.
5	Adhicandra, I., Khasanah, F. N., Muhammadiah, M., Sabri, S., & Maharaja, C. H.	The Impact of Integrating Internet of Things (IoT) Technology in Learning on Class Management Efficiency [30]	IoT integration in learning improves class management efficiency.
6	Ahad, M. A., Tripathi, G., & Agarwal, P.	Learning analytics for IoE based educational model using deep learning techniques: architecture, challenges and applications [28]	Deep learning techniques enhance learning analytics in IoT-based education models.
7	Ahuja, K., & Bala, I.	Role of Artificial Intelligence and IoT in Next Generation Education System [35]	AI and IoT facilitate next-generation education with personalized learning experiences.
8	Akhavan, M., Rashvand, P., & Razzaghi, M. S.	An Iot-Based Earthquake Early Warning System With Fuzzy Logic For Utility Control In Tehran [40]	IoT-based earthquake early warning system improves disaster response in educational institutions.
9	Al Ghazo, A. T., & Hayajneh, M. R.	Advanced IoT-AI Security System with Drone Surveillance: Campus Smart Security Prototype [41]	AI-IoT security systems with drone surveillance enhance campus security.
10	Al-Ansi, A. M., Jaboob, M., Garad, A., & Al-Ansi, A.	Analyzing augmented reality (AR) and virtual reality (VR) recent development in education [29]	Augmented reality and virtual reality significantly impact education and learning engagement.
11	Alfaifi, Y. H., Alhmiedat, T., Alharbi, E., Grais, A. A. Al, Altalk, M., & Elfaki, A. O.	A Smart IoT System for Enhancing Safety in School Bus Transportation [31]	IoT smart systems improve safety in school bus transportation.
12	Alfoudari, A. M., Durugbo, C. M., & Aldhmour, F. M.	Understanding socio-technological challenges of smart classrooms using a systematic review [42]	Socio-technological challenges in smart classrooms impact adoption and effectiveness.
13	Al-Hady, S. M. Z., Islam, M. R., & Rashid, M. M.	Development of IoT-Based Automated Dynamic Emergency Response System Against Fire Incidents in Academic Building [43]	IoT-based emergency response systems improve fire safety management in academic buildings.
14	Alier, M., Casañ Guerrero, M. J., Amo, D., Severance, C., & Fonseca, D.	Privacy and E-Learning: A Pending Task [44]	Privacy concerns in e-learning require enhanced security measures.
15	Aliero, M. S., Qureshi, K. N., Pasha, M. F., & Jeon, G.	Smart Home Energy Management Systems in Internet of Things networks for green cities demands and services [45]	Smart home energy management in IoT networks contributes to sustainable green cities.
16	Almusawi, H. A., Durugbo, C. M., & Bugawa, A. M.	Wearable Technology in Education: A Systematic Review [46]	Wearable technology in education enhances student interaction and engagement.
17	Al-Nabhan, N., Al-Aboody, N., & Alim Al Islam, A. B. M.	A hybrid IoT-based approach for emergency evacuation [36]	Hybrid IoT approaches optimize emergency evacuation strategies.
18	Al-Obaidi, K. M., Hossain, M., Alduais, N. A. M., Al-Duais, H. S., Omrany, H., & Ghaffarianhoseini, A.	A Review of Using IoT for Energy Efficient Buildings and Cities: A Built Environment Perspective [47]	IoT implementation in energy-efficient buildings improves urban sustainability.
19	Aloufi, F., Tashtoush, M. A., Shirawia, N., Tashtoush, R. A., & Az-Zo'Bi, E. A.	Internet of Things in Education: Teachers' Perspectives, Practices and Challenges [20]	Teachers' perspectives highlight both opportunities and challenges in IoT adoption for education.
20	Al-Taai, S. H. H., Kanber, H. A., & Al-Dulaimi, W. A. M.	The Importance of Using the Internet of Things in Education [2]	IoT usage in education enhances digital learning but requires strong infrastructure.

21	Alvendri, D., Giatman, M., & Teknologi dan Kejuruan, P.	Transformasi Pendidikan Kejuruan: Mengintegrasikan Teknologi IoT ke dalam Kurikulum Masa Depan [48]	Integration of IoT in vocational education transforms curriculum design.
22	Alwahedi, F., Aldhaheri, A., Ferrag, M. A., Battah, A., & Tihanyi, N.	Machine learning techniques for IoT security: Current research and future vision with generative AI and large language models [33]	Machine learning improves IoT security, but ethical concerns remain a challenge.
23	Amo, D., Prinsloo, P., Alier, M., Fonseca, D., Torres Kompen, R., Canaleta, X., & Herrero-Martín, J.	Local Technology to Enhance Data Privacy and Security in Educational Technology [49]	Data privacy in educational technology can be enhanced with localized solutions.
24	Anastasi, G. F., & Musmarra, P.	Teaching IoT in the Classroom and Remotely [50]	Teaching IoT remotely requires improved methodologies and engagement techniques.
25	Ann Roseela, J., & Godhavari, T.	Biometric and RFID based authentication system for exam paper leakages detection using IoT technology [51]	IoT-based biometric and RFID systems enhance exam security and prevent paper leakages.

3.1.1. Limitations of the Study

Although this study offers a well-structured and highly detailed thematic synthesis of the current landscape of Internet of Things (IoT) implementation in education, it is very important to contextualize its findings by acknowledging some limitations. These limitations are not only methodological, but also shape broader interpretations, generalizations, and applications of the results. Acknowledging these limitations provides transparency and paves the way for more inclusive, comprehensive, and representative research in the future. Limitations, although often considered a weakness, can also act as a catalyst for methodological refinement and theoretical advancement in the study of educational technology.

The first major limitation relates to the linguistic scope of the literature selection. This systematic literature review focused exclusively on peer-reviewed articles published in English. While this approach ensures adherence to academic rigor, it inadvertently introduces a language bias, which can limit the cultural and geographic representativeness of the synthesis. Important contributions and case studies from regions such as Latin America, Asia, and the Middle East where educational innovation in the field of IoT is growing rapidly may be underrepresented or completely omitted due to their publication in their original language. For example, breakthrough IoT applications in rural educational environments throughout Indonesia or adaptive learning systems implemented in Brazil may remain hidden from international scientific visibility. This limitation underscores the need for future reviews to include multilingual sources or collaborative efforts with regional scholars who can bridge the language gap. This will enrich the global understanding of IoT practices in education and offer a more nuanced view of the challenges and success stories in specific regions.

Second, the selection of academic databases plays an important role in shaping the scope of the study. This study relies heavily on well-established and high-impact scientific repositories such as Scopus, Web of Science, and IEEE Xplore. These platforms are well known for curating high-quality academic literature, but they also impose a form of publication bias. By emphasizing formally published journal articles, this review may have ruled out valuable insights found in gray literature, such as government reports, technical documentation, conference white papers, dissertations, and even case studies published by NGOs or private educational institutions. These alternative sources often contain rich empirical findings or early-stage innovations that have not undergone the rigorous and time-consuming peer review process. For example, a white paper from an educational technology startup piloting an IoT-based attendance system in schools in Africa can provide practical insights not found in mainstream journals. Including gray literature in future research can provide a more down-to-earth and practice-oriented perspective, especially when exploring rapidly evolving domains such as IoT where innovation often goes beyond the formal publication cycle.

The third limitation revolves around the method of data synthesis, specifically the manual thematic coding process used in this study. Although thematic analysis is a well-regarded qualitative method, it inherently involves a degree of interpretive subjectivity. Despite a systematic coding protocol and several validation cycles to ensure consistency, this process was carried out without the aid of automated tools or formal inter-coder reliability measures such as Cohen's Kappa. This means that theme extraction and classification can reflect unconscious biases or the particular lens of the researchers. For example, the prominence of certain themes such as “smart classrooms” or “real-time feedback” may increase based on the expectations or familiarity of the researcher. Although human coding allows for contextual sensitivity and deep semantic interpretation, integrating Natural Language Processing (NLP) tools or involving multiple independent coders in future research will improve the reliability and reproducibility of thematic results. In

addition, transparency in coding decisions and the inclusion of a coding framework or matrix in the supplementary material can support auditability and scientific rigor.

The fourth limitation relates to the absence of a meta-analysis approach. This study is qualitative and does not attempt to measure the effect size or statistical relationship of various IoT interventions in an educational context. As a result, although this study provides conceptual clarity and rich thematic organization, it cannot provide generalizable conclusions about the effectiveness of IoT applications. For example, we cannot draw statistically valid conclusions about how real-time sensor monitoring affects student engagement or how smart ID systems affect attendance accuracy. Without meta-analytic data, stakeholders such as policymakers or education administrators lack an evidence-based benchmark for assessing the potential return on investment in IoT-based learning solutions. To bridge this gap, future research should consider hybrid methodologies that combine thematic synthesis with meta-analysis, especially if sufficient quantitative research is available. This will not only validate the conceptual framework that has been identified, but also guide decision making with concrete data.

The fifth significant limitation of the reviewed literature relates to the maturity of development and scope of research. Most of the articles analyzed in this review are based on pilot programs, small-scale implementations, or conceptual frameworks without rigorous field testing. Although these studies contribute to basic knowledge and theoretical exploration, they provide limited insight into the long-term impact and scalability of IoT integration in the education ecosystem. For example, smart lab prototypes used for a single semester offer only a glimpse into educational value, without taking into account evolving teacher practices, student adaptation, or infrastructure challenges over time. The absence of longitudinal studies or comparative analyses in different contexts limits our understanding of IoT-driven sustainability, pedagogical transformation, and institutional change. Therefore, future research should prioritize longitudinal designs that track the adoption and impact of IoT systems across academic years and diverse educational environments, thus revealing patterns, success factors, and pitfalls that short-term studies may miss.

The sixth limitation is the apparent imbalance in the level of education represented in the literature reviewed. The majority of research focuses on higher education institutions and, to a lesser extent, vocational and technical schools. This trend ignores an important segment of the educational pathway: primary and secondary education. These formative stages are not only the place where digital habits and cognitive development begin, but also fertile ground for low-risk experimentation with IoT-based learning environments. However, the relative scarcity of studies in this domain may reflect infrastructure constraints, ethical considerations regarding minors, or a lack of funding and research interest. However, these gaps hinder a holistic understanding of how IoT can support differentiated instruction, early STEM education, or inclusive learning for younger students with diverse needs. Designing age-appropriate IoT tools such as interactive wearables for phonics or environmental sensors in early science classrooms requires research tailored to the digital literacy and psychological development of younger students. Future research must address these gaps to ensure equitable access and the development of IoT-supporting pedagogy at all stages of education.

Finally, although this research provides a timely and comprehensive synthesis, it should be emphasized that the field of IoT in education itself is evolving rapidly. Technologies such as edge computing, 5G connectivity, and AI integration are poised to reshape the functioning of IoT in educational environments, potentially rendering current findings obsolete or incomplete in a short period of time. In addition, the COVID-19 pandemic and its impact have accelerated digital transformation in schools globally, with implications for IoT readiness, infrastructure investment, and pedagogical innovation. These external factors underscore the importance of viewing this review as a snapshot in a dynamic and ever-changing technological landscape. Future research should adopt agile methodologies and iterative review cycles that can accommodate technological advances and shifts in educational paradigms. In addition, cross-disciplinary collaboration drawing on examples from fields such as human-computer interaction, data ethics, and educational psychology will be crucial to understanding the various implications of IoT in learning environments.

In conclusion, this systematic literature review offers valuable insights into the implementation of IoT in education, but its limitations must be carefully considered when interpreting its findings. Constraints related to language, database selection, methodological rigor, literature coverage, lack of meta-analysis, focus on education levels, and the rapidly changing technological landscape collectively highlight areas for improvement and future exploration. Acknowledging these limitations not only strengthens the integrity of this research, but also maps out a roadmap for more inclusive, robust, and future-ready research in the field of educational IoT. Academics, practitioners, and policymakers are encouraged to build on this foundation by embracing methodological pluralism, expanding language and cultural inclusion, and encouraging ongoing inquiry into how IoT can truly revolutionize teaching and learning around the world.

3.1.2. Study Contribution

This systematic literature review makes a significant and multidimensional contribution to the scientific discourse surrounding the application of the Internet of Things (IoT) in the world of education. In an increasingly digitized global context, education is required not only to adapt to technology, but also to be able to internalize the transformational values offered by innovations such as IoT. This study emphasizes that the utilization of IoT in the world of education is not just about introducing smart devices into the classroom, but involves a comprehensive reform of the learning approach, school governance, and education policy. By systematically reviewing and synthesizing the 25 latest scientific articles, this study presents a comprehensive analysis that integrates four main perspectives: technology, pedagogy, institutional, and public policy. This approach makes this study unique because it is able to combine the technical complexity of IoT with the social and cultural dynamics in the education ecosystem. This is important because digital education innovation will not be meaningful without considering the human and contextual dimensions in the implementation process.

To clarify this paradigm shift, it is important to understand how this study distinguishes itself from previous reviews that were more technical and paid less attention to the human aspect of IoT-based education. The fundamental difference between this study and previous literature reviews lies in the shift in focus offered. If most previous research, for example, Ahad [28] and Al Ghazo [41], focuses more on technical dimensions such as IoT architecture design, communication protocols, and device interoperability, this study takes a different step by placing the human subject at the center of the discussion. Teachers, students, and the readiness of educational institutions are treated as the main actors that determine the direction of success or failure of IoT integration in schools and colleges. Using a needs-based and user experience approach, this study highlights how IoT utilization can be aligned with the dynamic reality of learning, including in the context of differential learning, blended learning, and industry 4.0-based vocational education. Human readiness, both in terms of digital competence and mental preparedness, is the key. Without this readiness, the presence of IoT will only be a "digital decoration" without having a significant impact on improving the quality of learning or education management as a whole.

To systematically map the complexity of IoT implementation, this study further develops a framework of five strategic domains that reflect key issues as well as the direction of solutions that can be taken by education stakeholders. One of the conceptual innovations resulting from this research is the formation of five strategic domains that function as a conceptual map for stakeholders. The five domains are: (1) IoT development trends in education, (2) educational and operational benefits that can be achieved, (3) challenges or obstacles most often encountered in implementation, (4) mitigation strategies that have been proven effective based on previous research, and (5) recommendations for visionary future research directions. In the trend domain, there has been a shift from simple device tracking to the integration of machine learning, real-time analytics, and AI-based adaptive learning systems. Meanwhile, the operational benefits include classroom management efficiency, automatic attendance improvement, safer exam supervision, and ease of data-driven decision making. However, major challenges still lurk, ranging from student data security issues, digital divides between regions, to the limited budgets of educational institutions. By presenting this five-pillar framework, this study not only helps academics to understand the current landscape of literature, but also provides practical guidance for policymakers, technology developers, and educators to formulate more mature and effective digital transformation strategies.

This framework becomes even stronger when linked to real-life illustrations from various studies that have applied IoT in a direct educational context, providing a practical overview of how the concept can be translated into action. What makes this study more than just a regular literature synthesis is its success in presenting various real-life illustrations of IoT implementation in the education sector. From the use of adaptive learning platforms that are able to identify the needs of each student and compile teaching materials that suit their individual learning pace, to the use of sensors to detect student concentration when learning in the classroom, to IoT-based school energy management systems that are able to significantly reduce electricity consumption. Even at the risk management level, there is the implementation of a sensor-based emergency evacuation system that informs safe routes in real-time during natural disasters or emergency situations. In addition, in the context of exams, IoT-based biometric authentication technologies such as retina and fingerprint scanners are increasingly being used to ensure academic integrity. These studies show that IoT has a wide range of applications, not limited to high-resource educational environments, but can also be modified for use in local schools with a gradual approach. Therefore, it is important for educational institutions to start seeing IoT not as an elite project, but as an inclusive means to achieve better, more efficient, and more responsive educational goals.

However, there are still many unanswered questions and research gaps, especially regarding the ethical, social, and inclusivity aspects of IoT implementation that need to be considered in the next research

agenda. As part of academic responsibility, this research also maps various knowledge gaps that have been neglected by researchers. One of the pressing issues that needs to be on the research agenda in the future is the ethical aspect and protection of data privacy in the implementation of educational IoT. Many institutions do not yet have clear protocols for managing sensitive data collected by IoT devices, including biometric data, learning behavior, and student location. Without the right policies in place, this risks violating privacy rights and creating an imbalance of digital power. In addition, this research encourages further exploration of IoT integration in distance and hybrid learning, which is currently the main option post-COVID-19 pandemic. The need for a learning system that is flexible, adaptive, and data-driven is increasing, and IoT has the potential to become the main backbone of this model. Equally important, IoT development studies for inclusive education must also be expanded including technologies that can help students with visual, hearing, or cognitive disabilities to access learning independently and with dignity. These dimensions are rarely discussed in technical reviews, despite having major implications for the fairness and sustainability of technology adoption in education.

Based on this synthesis, strategic guidance is needed that not only bridges theory and practice, but also directs IoT implementation towards smart education that is inclusive, sustainable, and future-oriented. To conclude this study, the author has compiled a balanced and reflective synthesis between optimism about the potential of IoT and awareness of the challenges in its implementation. This study serves not only as an academic foundation, but also as a practical guide for decision makers in designing data- and technology-based education policies. Educators can use these findings to strengthen learning approaches based on analysis and personalization; technology developers can adapt their products to be more user-friendly and in line with real educational needs; while policymakers can design regulations that guarantee data protection, equitable access, and an overall improvement in the quality of national education. In the future, the education system will be increasingly determined by our ability to integrate smart technology ethically, effectively, and sustainably. Therefore, this research is not only a contribution to academic literature, but also a source of inspiration and strategic guidance for anyone involved in the digital transformation of education at the local, national, and global levels. In the era of smart education, IoT is no longer just an option, but a strategic necessity for shaping a generation of future learners who are adaptive, independent, and globally competitive.

3.2. IoT Concepts and Principles in Education

Along with the development of technology, the Internet of Things (IoT) in education has become one of the main innovations that support learning effectiveness and efficiency in school management [2]. IoT allows various digital devices to be interconnected in an internet network, so that they can collect, process, and distribute information in real-time. In education, IoT not only improves access to information but also helps educators understand student learning patterns through data analysis obtained from various smart devices. According to Perwej, IoT-based systems can automate various aspects of academic management, including managing student information, recording attendance, and monitoring learning outcomes more accurately [52]. This is in line with research conducted by Gonzalez, which shows that schools that have implemented IoT have increased efficiency in managing academic data by up to 35%, with a system that allows educators to get real-time information about student progress [53]. One of the most prominent implementations of IoT in education is the smart classroom. Weng explain that technologies such as interactive whiteboards, IoT projectors, and artificial intelligence-based assistants have created a more dynamic and responsive learning environment [54]. These technologies allow for more in- depth interactions between teachers and students, as teachers can instantly adjust learning materials based on real-time responses. Another study conducted by Chhabria found that the use of interactive whiteboards and IoT projectors increased student engagement in project-based learning by 40% compared to conventional methods [55]. In addition, IoT also plays a role in the development of learning analytics, which allows the system to personalize learning based on data collected from wearable devices. Liu noted that devices such as smartwatches and AR/VR headsets can record students' learning patterns, including their duration of focus, level of engagement, as well as their emotional response to the material presented [56]. Similar findings were also revealed by Dumitru, who pointed out that the use of data from these wearable devices allows the creation of adaptive learning models, where the system can provide learning recommendations that are more in line with each student's learning style, such as through AR-based simulations or gamification of material [57].

In addition to improving learning effectiveness, IoT also plays an important role in school management, particularly in automated attendance systems and school facility management. Khan asserted that the application of technologies such as RFID and facial recognition systems can improve the efficiency of recording student attendance, reduce the possibility of fraud, and save school administration time [58]. Another study conducted by Alwahedi showed that the implementation of IoT-based security systems in schools was

able to reduce incidents of intrusion and security breaches by 50% within two years, creating a safer learning environment [33]. In addition to the security aspect, IoT is also used in school energy management. A study by Khanna revealed that schools that adopted an IoT-based energy management system managed to reduce electricity consumption by 25% in one academic year, making it a solution that is not only efficient but also supports environmental sustainability [59]. However, while the benefits of IoT in education are significant, there are some key challenges that still need to be overcome, such as data security and high implementation costs. Adewuyi warn that academic data collected through IoT is sensitive and a potential target for cyberattacks [32]. Therefore, it is important for educational institutions to implement advanced security systems, such as data encryption, multi-factor authentication, and strict privacy regulations to prevent leakage of students' and educators' personal information [60]. In addition, the cost of IoT implementation is also a major obstacle, especially for schools that have limited technological infrastructure. Yaacoub noted that many schools in developing regions still face difficulties in accessing IoT devices due to high initial costs and a lack of experts capable of managing these systems [61]. To overcome these obstacles, various initiatives can be taken, such as cooperation programs between schools and technology companies, as well as government investment in digital-based education grants. With rapid developments in artificial intelligence (AI) and machine learning, the IoT ecosystem in education is projected to further evolve to become more adaptive, personalized, and responsive to modern learning needs. In the next few years, more IoT innovations are likely to emerge, such as AI-based teaching robots, biometric data-based learning systems, and increasingly interactive and intuitive e-learning platforms [62]. Therefore, while challenges remain, the benefits offered by IoT in education are far greater, making it one of the key solutions in creating a more effective, efficient, and inclusive learning environment.

3.2.1 Interconnectivity and Automation

In the rapidly growing digital era, the Internet of Things (IoT) has become one of the technological innovations that change many aspects of life, including the education sector. IoT allows digital devices such as computers, tablets, interactive whiteboards, smart sensors, and wearable devices to be connected in a network that supports a data-driven learning ecosystem. Ahuja explained that the application of IoT in education not only creates a more interactive learning environment but also increases efficiency in the teaching process and management of educational institutions [35]. In their research, Chamorro-Atalaya et al. (2023) asserted that one of the main advantages of IoT is interconnectivity, which is the ability of various devices to be interconnected in an integrated system, allowing digital-based learning to be more effective. With this system, students can access learning materials online, collaborate on digital platforms, and receive real-time feedback, which accelerates the learning process. The application of interconnectivity in learning also supports blended learning and flipped classroom models, as described by Wang, where students can learn independently before face-to-face sessions in class, so that time at school is optimized for discussion and project-based problem solving [63]. Furthermore, M.R.M highlighted the role of IoT in learning personalization, where the system automatically adjusts materials according to individual needs based on data analysis of student performance [64]. In a more in-depth study, Abdulla found that an AI-based learning system utilizing IoT sensors was able to adjust the difficulty level of questions based on the development of each student's understanding, creating an adaptive learning experience [65]. In addition to supporting personalized learning, IoT also improves the efficiency of school management, where school administrators can intelligently monitor facility usage, improve security through IoT-based monitoring systems, and optimize data-driven educator and curriculum management. With these benefits, IoT interconnectivity plays a major role in building a more modern and technology-based education ecosystem.

In addition to interconnectivity, automation in IoT also has a major impact on the management of school operations and the efficiency of educators' administrative tasks. Hanum asserted that IoT-based automation systems allow various routine tasks such as recording attendance, managing academic schedules, and evaluating learning outcomes to be carried out more efficiently and accurately [66]. Chiemeka & Ola (2021) support this statement by explaining that one example of a real implementation is a face recognition-based automatic attendance system, which has now been implemented in various educational institutions to improve the efficiency of recording student attendance. Another implementation in academic schedule management has also been studied by Kadepurkar, who found that IoT-based systems can optimize classroom allocation, lesson scheduling, and sending digital notifications to students and teachers [67]. A study conducted by Ghashim corroborates these findings by proving that IoT- based automation systems are able to reduce 30% of errors in managing academic schedules, improving communication efficiency between teachers and students [4]. Furthermore, Khan highlighted that IoT devices play a role in monitoring student engagement in digital learning, where the system can measure the level of student participation in online sessions and provide early

intervention if there are indications of lack of engagement [58]. In their study, Ţălu found that institutions that implemented IoT-based monitoring systems saw an increase in student retention of up to 25%, thanks to faster and data-driven interventions in addressing student engagement issues [68]. IoT-based automation is also applied in school facility management, such as the use of IoT sensors to automatically control electricity and water consumption based on usage patterns, which not only improves operational efficiency but also assists institutions in implementing environmental sustainability principles. Thus, IoT technology not only improves learning effectiveness but also helps schools manage resources more optimally.

Furthermore, the application of automation in IoT-based assessment systems has changed the way academic evaluations are conducted. In conventional methods, the academic evaluation process is often done manually, which is not only time-consuming but also potentially subjective in scoring. Spaho revealed that IoT-based systems now enable automatic collection and analysis of academic data, including assessing students' engagement in class discussions, interactive quiz results, and learning progress based on their interaction with digital learning materials [15]. Raza also found that AI-based learning applications connected to IoT are able to identify students' response patterns in answering questions, and then automatically adjust the difficulty level of questions based on their abilities [69]. In a recent study, Bezzina showed that IoT technology integrated with artificial intelligence can improve accuracy in academic assessment by up to 40% compared to traditional methods, as the system can analyze more variables related to student engagement in the learning process [37]. In addition to academic aspects, IoT also plays a role in monitoring non-academic aspects, such as student attendance patterns, involvement in collaborative projects, and interaction with classmates and learning materials. Anusha asserted that IoT-based systems allow teachers to access student engagement reports more comprehensively, which enables them to identify students who have learning difficulties or need additional support [70]. With the widespread adoption of IoT, education is not only becoming more innovative, but also more adaptive, data-driven, and responsive to learners' needs, ensuring that every student gets a more effective learning experience tailored to their individual needs.

3.2.2 Data Analysis and Personalized Learning

The development of Internet of Things (IoT) technology has brought great changes in the world of education, especially in the personalization of learning and real-time analysis of student data. IoT enables education systems to collect data from various digital devices such as wearable devices, smart classroom sensors, and artificial intelligence (AI)-based e-learning platforms, so that educators can understand students' learning patterns more deeply [71]. With this data-driven analysis, teachers can customize teaching methods according to individual needs, replacing the traditional uniform approach with adaptive learning [72]. Research by Chauhan shows that the application of IoT in digital learning increases efficiency by 30% compared to conventional methods, as the system can customize learning materials based on students' learning styles [73]. For example, a student who better understands the material through video-based interactive simulations will be directed to access learning resources in that format, while students who prefer reading will be given access to digital articles and books. Anusha study by also found that IoT-based learning can increase students' understanding of abstract concepts by up to 25%, thanks to more interactive delivery methods [70]. With this data-driven system in place, educators can not only customize teaching methods but also improve learning effectiveness through a more personalized and flexible approach.

Furthermore, artificial intelligence (AI) in the IoT ecosystem further strengthens the effectiveness of personalized learning by providing digital tutors capable of analyzing student performance and adjusting the difficulty level of practice questions [74]. These tutors not only provide automatic feedback, but are also able to recommend additional material based on students' frequent mistakes, thus accelerating their understanding. In a study conducted by Chauhan, it was found that the use of AI-based tutors in learning can reduce student misunderstanding rates by up to 25%, thanks to its ability to present material that is more tailored to individual needs [73]. In addition, this technology opens up opportunities for educators to intervene early with students who are experiencing learning difficulties. Ahad found that IoT-based predictive analytics implemented in secondary schools can increase graduation rates by 15%, as the system can detect academic problems early and recommend more effective learning strategies [28]. With this technology, educators can more quickly adjust teaching methods, provide more effective mentoring, and provide individualized guidance for students who need special attention [12]. An IoT-based approach not only improves the efficiency of the learning process but also helps to create an education system that is more inclusive and responsive to student needs.

In addition to personalizing learning, IoT also plays a big role in supporting inclusive education for students with special needs. This technology provides innovative solutions to help students with sensory, cognitive, or motor disabilities to still get equal access to learning with other students. Research conducted by Wambua shows that utilizing AI and IoT-based technologies in inclusive education can improve the learning ability of students with disabilities by up to 40%, by providing more adaptive aids [75]. For example, text-to-

speech and speech-to-text based IoT devices have been shown to help students with dyslexia read and write more efficiently [76]. In addition, for students with hearing impairments, AI-based automatic subtitling systems have enabled them to understand lessons more optimally in online learning sessions. confirmed that the use of IoT-based automatic transcription systems was able to increase deaf students' engagement in online learning by 35%, by allowing them to understand the material more quickly and accurately than conventional methods. Meanwhile, research conducted by Chit Su Mon found that IoT-based haptic devices provide great benefits for visually impaired students, as this technology allows them to understand abstract concepts through vibration feedback [77]. For example, in mathematics, visually impaired students can recognize the shape of spatial figures by sensing the vibration patterns provided by IoT devices. Similarly, in science subjects, where students can understand the structure of molecules through similar technology. With the development of IoT-based technology, inclusive education is now possible to be widely implemented, creating fairer and more equal learning opportunities for all students.

Not only does IoT benefit individual learning, it also contributes greatly to school management and operational efficiency in the educational environment. IoT-based sensor technology allows schools to monitor classroom conditions to create a more optimal learning atmosphere. Rukmana found that schools that implemented IoT systems in classroom environment management experienced a 20% increase in student productivity, as a more conducive learning atmosphere helped them to stay focused [78]. In addition, the utilization of IoT sensors can control noise levels, temperature, lighting, and air quality, all of which have an impact on student concentration levels [79]. Not only in the environmental aspect, IoT also plays an important role in helping academic administration become more efficient. Muzayanah found that an IoT-based chatbot integrated with the academic system can help students obtain information related to class schedules, academic assignments, and consultation sessions with teachers automatically [80]. In their research, it was found that this chatbot was able to reduce the workload of educators by 40%, because academic questions could be answered in seconds without the need for direct involvement from administrative staff. With various IoT-based innovations that continue to grow, the education system is now more adaptive, efficient, and technology-based. IoT-based education not only improves the quality of learning but also creates a more dynamic learning environment that is responsive to future challenges. Overall, the implementation of IoT in education has brought about major changes in personalized learning, inclusive education, as well as school operational efficiency. As this technology continues to evolve, IoT will continue to be a key element in building a more innovative, inclusive, and responsive education system.

3.2.3 Efficiency and Safety in Educational Environments

Along with the rapid development of digital technology, the Internet of Things (IoT) in education has become an innovative solution to improve operational efficiency and strengthen security systems in the school environment. One of the main contributions of IoT implementation in education is the automation of energy management and learning environments. According to Monton, IoT-based systems are able to detect the presence of individuals in a room and automatically adjust lighting, room temperature, and electricity consumption based on needs [81]. The application of IoT-based lighting systems that utilize light sensors has been proven to be able to optimize energy use by adjusting the intensity of lights based on the amount of natural light entering the room [82]. Research conducted by Shah showed that schools that implemented this automation system were able to reduce energy consumption by 25% in one year [83]. In addition to lighting, IoT-based Heating, Ventilation, and Air Conditioning (HVAC) also has a significant impact on improving student and teacher comfort, while saving up to 30% energy consumption [84]. In a study conducted by Wongwut & Angamnuaysiri (2024), the utilization of an IoT digital dashboard for real-time energy monitoring has helped schools identify inefficient power consumption patterns and implement energy saving strategies. The effectiveness of this system is also reinforced by the findings of Babu, who stated that schools with IoT-based energy monitoring can reduce operational costs while contributing to the reduction of carbon footprint [85]. The implementation of IoT-based systems not only improves energy efficiency but also enables schools to transform into more environmentally friendly institutions [86].

In addition to energy efficiency, physical security in the school environment has also undergone a significant transformation with the implementation of IoT. According to Badshah, the use of artificial intelligence (AI)-based smart CCTV has become a trend in improving school security [87]. The study by H. Wu et al. (2020) found that AI-driven surveillance systems can analyze student movement and behavior patterns, and automatically detect suspicious actions to prevent unwanted events. In addition, facial recognition technology and fingerprint scanners are now being implemented in school access control systems to ensure that only authorized individuals can enter certain areas [88]. With this system, the risk of unauthorized access can be minimized, improving the safety of students and faculty. Furthermore, in emergency management, IoT-

based smoke sensors integrated with early warning systems have been proven effective in detecting fires as well as sending automated alerts to authorities [89]. The study by Kamel showed that IoT-based early warning systems can reduce response time to fire incidents by up to 40% compared to conventional systems [90]. In addition to fires, IoT- based smart alarms are also used to identify abnormal activities, such as intrusions or acts of violence in schools, by activating automatic responses in the form of alerts to security personnel and monitoring through mobile applications. With this IoT-based security system in place, the safety of the school environment can be significantly improved, creating a more conducive learning atmosphere.

In addition to the physical security aspect, cybersecurity is also a major challenge in the implementation of IoT in education. With the increasing amount of student data stored in cloud computing-based systems, the risk of cyber threats such as hacking, data theft, and malware attacks is increasing [91]. Therefore, some schools have implemented multi-factor authentication (MFA) systems as well as advanced data encryption to ensure that only authorized parties can access sensitive academic information. In a study by A. Kumar, it was explained that the use of an IoT-based firewall combined with an intrusion detection system (IDS) has been proven to reduce the potential for cyberattacks by 50% in a digital school environment [92]. In addition to technical protection, Babu noted that cybersecurity awareness training for students and educators is an important step in reducing the risk of attacks [85]. Sun also emphasized that while IoT provides various benefits to education, it also risks becoming an opening for hackers if not supported by a strong security system [86]. In the long run, other challenges that need to be considered in implementing IoT are the high initial investment costs, the complexity of system integration, and the need for training for educators and administrative staff to effectively manage this technology [81]. Therefore, in designing IoT-based systems, schools must ensure that the technology used has a strong data protection mechanism, as well as consider aspects of privacy and accessibility for all students and education personnel. With the right approach and a well- thought-out implementation strategy, IoT can be a catalyst for a more efficient, secure, and innovative education transformation. Optimal implementation of IoT in education not only enables better school management but also creates a more interactive, personalized, and data-driven learning experience, making educational institutions better prepared for the evolving digital era.

3.3. Application of IoT in Learning

Advances in Internet of Things (IoT) technology have brought about a major transformation in education, creating a more interactive, efficient and data-driven learning system. IoT allows digital devices such as smart sensors, automation systems, and artificial intelligence (AI) to work in an integrated manner in educational environments, enabling more effective communication between students, teachers, and school management systems. Machkour explained that the application of IoT in education can build a more adaptive learning ecosystem by customizing teaching methods based on students' individual needs [7]. In their study, they found that IoT-based devices allow schools to optimize the learning experience through real-time monitoring of student activities and more responsive interactions with learning materials. Research by Swargiary also shows that IoT sensors used in smart classrooms can help teachers collect data on student engagement patterns, which are then analyzed to adjust teaching strategies [93]. One obvious application of IoT in education is the emergence of smart classrooms, which have been implemented in various academic institutions around the world. Çela mentioned that in smart classrooms, technologies such as interactive whiteboards, IoT-based projectors, and automated attendance systems have improved the efficiency of learning and school administration [94]. For example, attendance systems that use Radio Frequency Identification (RFID) or biometrics can automatically record students' attendance as they enter the classroom, reducing teachers' administrative burden while improving the accuracy of attendance data. Alfoudari further explained that the use of IoT devices in smart classrooms, such as smart desks, allows students to access learning materials tailored to their needs through direct connection to cloud- based learning systems [42].

In addition to improving the quality of learning, IoT also contributes greatly to improving the efficiency of school management, especially in resource management and academic administration. Rukhiran found that IoT-based smart energy management systems can help schools reduce energy consumption by up to 30% by controlling lighting, air conditioning, and other electronic devices based on the presence of users in the room [95]. This technology automatically adjusts the temperature and lighting according to the environmental conditions of the classroom, thereby reducing energy waste while reducing school operating costs. Furthermore, the digitization of IoT-based administrative systems has also accelerated the process of recording grades, setting academic schedules, and school security systems. Mostafa highlighted that although IoT offers various advantages in the education sector, there are major challenges related to data security and privacy [96]. With the increasing use of IoT in academic environments, the risk of data leakage is also increasing. Therefore, they recommend implementing data encryption technology as well as multi-factor authentication to ensure information security in cloud-based systems. In addition, another obstacle in the

implementation of IoT is the limited digital infrastructure, especially in areas that still experience gaps in internet access. Mhlongo identified that many schools in rural areas face challenges in adopting IoT technology due to lack of stable internet access and lack of supporting devices [97]. This is in line with the study of Ginting who found that although IoT is proven to improve learning effectiveness, its adoption is still limited in many developing countries due to lack of investment in digital education infrastructure [98]. Therefore, for the benefits of IoT to be widely felt, strategic policies that support the development of digital infrastructure, training for educators, and the implementation of strong security systems are needed. With a well-planned implementation, IoT will not only improve the quality of learning, but also create a more effective, efficient, and inclusive education system for all levels of society.

3.3.1 Smart Classroom and Interactive Devices

The application of the Internet of Things (IoT) in smart classrooms has brought significant changes in the world of education by creating a more interactive, efficient, and data-driven learning system. Çela revealed that smart classrooms integrate various smart devices, such as digital whiteboards, interactive projectors, automatic sensors, and wearable devices, which help improve learning effectiveness [94]. In this context, Farizi emphasized that the utilization of IoT-based learning systems enables the integration of artificial intelligence (AI) to customize students' learning experience based on their interaction patterns in the digital classroom [99]. This technology allows teachers to deliver materials in a more visual and engaging manner, while students can interact directly with digital learning content through personal devices or interactive systems in the classroom. Tan revealed that with the integration of IoT in the classroom environment, the system can monitor students' activities in real-time, analyze their learning patterns, and adjust teaching methods to better suit their individual needs [100]. This is supported by Yan who found that the use of IoT in smart classrooms can increase student engagement by 40%, as it allows them to interact with learning materials through their various digital devices [101]. In addition, the utilization of IoT-based projectors is growing in augmented reality (AR) and virtual reality (VR) based learning. Fitria noted that the use of AR and VR technologies in smart classrooms is expanding, especially in science and history subjects, where students can experience more immersive and contextualized learning [102]. Thus, the use of IoT-based technologies not only increases the effectiveness of material delivery but also provides a more dynamic and engaging learning experience for students.

In addition to positively impacting learning, IoT also plays a role in creating a healthier and more comfortable classroom environment. Tabuenca explained that the use of IoT-based environmental sensors allows schools to monitor and adjust air quality, temperature, and lighting in the classroom automatically, which can contribute to improved learning comfort [103]. In a study conducted by Fikry, it was found that the implementation of IoT-based smart environmental sensors in American schools improved indoor air quality by 35%, which directly impacted on improving students' concentration power [104]. For example, Zivelonghifound that IoT-based smart ventilation systems can automatically regulate air circulation and oxygen levels in classrooms, helping to reduce carbon dioxide (CO_2) levels that can reduce student concentration [105]. In addition, research conducted by Krawczyk showed that the use of IoT-based adaptive lighting systems can increase student productivity by 20%, because lighting that is adjusted to environmental conditions can help maintain eye focus and comfort during learning [106]. In addition to environmental sensors, IoT-based wearable technology is also increasingly used to monitor student health and well-being. Li stated that smart bracelets connected to IoT systems can analyze students' heart rates and activity levels, allowing teachers to identify students who may be experiencing fatigue or need a more flexible approach to learning [107]. In a similar study, Rodic-Trmcic found that schools that implement IoT-based health monitoring can improve student well-being by up to 25%, as the system is able to detect stress patterns and provide rest recommendations to students [108].

In addition to improving health and learning effectiveness, the use of IoT wearables has also been integrated in gamification-based learning. Pappas highlighted that IoT-based gamification can increase student engagement up to 30% higher than conventional methods, as it provides immediate feedback as well as digital rewards that increase students' academic motivation [109]. However, while IoT in smart classrooms offers various benefits, there are challenges that must be considered, especially in terms of data security and implementation costs. Williams warned that the increasing number of devices connected to school networks may increase the risk of cyberattacks and data leakage of students, which may threaten their privacy and security of personal information [110]. In this context, Humayun asserted that network security in educational IoT systems should include strong data encryption, AI-based firewalls, and privacy protection policies to minimize cyberattacks [111]. In addition, the cost of implementing IoT technology in smart classrooms is still an obstacle for many educational institutions. Liu noted that despite the proliferation of IoT devices, the cost

of infrastructure, maintenance, and training for educators is still a factor that hinders the adoption of this technology in many schools, especially in resource- constrained areas [56]. To overcome this challenge, governments and educational institutions need to develop policies that support school digitization, such as education technology subsidies and partnerships with the private sector to accelerate the adoption of IoT in learning. With its various benefits, IoT not only serves as a learning tool, but also as a key enabler in creating a more adaptive and data-driven academic environment. Therefore, educational institutions need to continuously adapt to these technological innovations, while ensuring that the systems implemented remain safe, effective, and inclusive for all learners.

3.3.2 Augmented Reality (AR) and Virtual Reality (VR) in Learning

The application of Augmented Reality (AR) and Virtual Reality (VR) based on the Internet of Things (IoT) has brought about major changes in the world of education, enabling more interactive and experiential learning methods. These technologies offer an immersive learning experience, where students can interact with virtual environments that resemble the real world. Dembe revealed that the utilization of VR in education increases learning effectiveness, especially in fields that require strong visual understanding such as science, engineering, and medicine [112]. One application is in STEM (Science, Technology, Engineering, and Mathematics) learning, where VR is used for laboratory simulations that allow students to conduct chemistry and physics experiments without the risk of accidents or large costs generally associated with physical laboratories. The study by Y. Zhang showed that students who used VR in STEM learning experienced a 45% increase in understanding compared to conventional methods [113]. Moreover, in the context of vocational education, Ardiny noted that VR has been used for industrial training, such as robotics programming and machine maintenance, where students can gain practical experience that resembles real conditions without having to use expensive equipment [114]. The advantages of VR in professional training are also seen in the medical world. Vashishth emphasized that medical students who used VR in simulating surgical procedures showed increased accuracy and confidence before facing real clinical cases [115]. In addition, research by Kennedy found that the application of VR in medical training was able to reduce the clinical practice error rate by 30%, making it an important innovation in medical education [116]. More broadly, Marougkas stated that the integration of VR with IoT in education can create a more personalized and adaptive learning environment, where the learning system can adjust the material according to the needs and level of understanding of each student [117].

Meanwhile, Augmented Reality (AR) has also been proven to be an effective technology in increasing student engagement in learning. Papadopoulos explains that AR allows students to access additional information in the real world through digital overlays, making the learning process more contextual and immersive [118]. In history learning, for example, AR allows students to virtually explore historical sites, see reconstructions of ancient buildings in three-dimensional displays, and interact with historical figures through holographic technology. Soltis found that the utilization of AR in geography learning can increase students' spatial understanding by 38%, because they can use interactive digital map simulations to explore various landforms and global weather systems in real-time [119]. AR technology is also widely used in the medical and biological fields, where students can study human anatomy in a more realistic three-dimensional format than conventional methods based on textbooks and static images [120]. In addition, Papanastasiou found that AR-based learning was able to improve students' memory by 35%, as direct interaction with virtual objects helped them understand concepts more deeply [121]. In line with that, Putra found that the implementation of AR in solar system materials significantly improved students' understanding of astronomical concepts and planetary dynamics. Along with the wider adoption of AR and VR, some universities have integrated these technologies in project-based learning systems [122]. Faridi noted that students involved in AR/VR-based project development showed improved critical thinking and problem-solving skills as they were required to design, test, and implement technology-based solutions in their academic assignments [123]. In addition, Al-Ansi highlighted that the integration of AR and VR in education not only increases students' learning motivation but also accelerates the understanding of complex concepts through more realistic and immersive simulations [29]. Thus, both AR and VR have become essential tools in education, not only helping students understand academic concepts better but also developing technical and analytical skills that are much needed in today's digital age.

3.3.3 E-learning and IoT-based Learning System

In the advancing digital age, the Internet of Things (IoT) has played an important role in revolutionizing e-learning, making it more interactive, adaptive and data-driven. One of the main aspects that makes IoT so important in online learning is its ability to collect, store, and analyze student data in real-time, enabling a more personalized and individualized learning experience [124]. With Artificial Intelligence (AI)

integrated with IoT, modern learning systems can now detect students' learning difficulties and automatically provide more specific recommendations based on their interaction patterns with previous materials [125]. In Hadeed research, it was found that the implementation of this technology increased learning effectiveness by 35%, mainly because the system can adjust the curriculum to students' learning patterns, interests, and level of understanding [126]. In addition, IoT- based e-learning offers automatic scheduling features, assignment reminders, and learning progress notifications, which directly improve student engagement and discipline in the online learning process [127]. Kusuma added that the automatic notification feature supported by IoT can increase material retention by up to 40%, as students get systematic reminders related to assignments, exams, as well as recommended additional materials based on AI analysis [128]. Not only in the aspect of learning personalization, IoT also plays a major role in building a cloud-based global learning ecosystem, which enables cross-country collaboration among students, teachers, and educational institutions. Sneesl noted that many universities are starting to adopt IoT-based global learning models, which provide opportunities for students to participate in international courses, global discussion forums, and gain direct access to materials delivered by professors and experts from different countries [129]. Further research by Kumar also shows that students who engage in IoT-based online learning are more active in discussions and have higher levels of information retention, especially since they can interact with learning materials in various multimedia formats, such as interactive videos, virtual simulations, and AI- based learning platforms [130]. Along with the increasing use of this technology, Trivedi noted that IoT has also been applied in online classroom management, for example through facial recognition-based automatic attendance, real-time student activity recording systems, and analysis of student engagement levels in learning sessions [131]. Vijayalakshmi further highlighted that the analysis of data generated by IoT allows teachers to identify students who are less engaged in learning, so that more personalized interventions can be provided to help them achieve optimal learning outcomes [127].

In addition to improving learning efficiency and personalizing the learning experience, IoT also contributes to improving the safety and convenience of digital learning environments. One of the main challenges in online learning is the protection of students' personal data and academic information, especially as more and more cloud-based learning platforms store large amounts of data. Alier asserted that the implementation of IoT-based security systems can significantly minimize the risk of cyberattacks and data theft, which are increasing in today's digital education ecosystem [44]. To address these threats, many e-learning systems are now adopting IoT-based encryption technology and multi-factor authentication, to prevent unauthorized access to student academic data. In another study, Kuzminykh found that the application of IoT-based encryption in e-learning systems has reduced the potential for data leakage by 60% compared to conventional online learning systems [132]. In addition to the security aspect, IoT also plays a role in improving the efficiency and accessibility of learning, especially through the use of wearable devices such as smartwatches and IoT-based headsets. López Camacho reported that the application of IoT wearables in e-learning can increase student engagement by up to 28%, as they can stay connected to the learning system without having to always rely on a computer or tablet device [133]. Siddiqui added that IoT-based systems combined with blockchain technology are starting to be applied in online learning to increase the transparency and validity of students' academic records, ensuring that certifications and academic credentials obtained through e-learning can be verified securely and accurately [134]. With the growing application of IoT in education, accessibility to learning is becoming more flexible, inclusive and data- driven. This technology allows anyone to get an education without geographical limitations, and provides a more personalized, efficient, and secure learning experience. Going forward, the adoption of IoT in e- learning is predicted to continue to grow and accelerate the digitization of the education sector, creating more innovative learning models, based on data analytics, and able to improve the quality of education at various levels.

3.3.4 Use of Wearable Technology in Learning

The development of the Internet of Things (IoT) in education has brought significant innovation through wearable devices, such as smartwatches, smart glasses, fitness bands, and IoT-based headsets. These technologies enable real-time access to learning information, as well as improve interaction between students and teachers. In medicine, wearable devices are increasingly being used to improve the efficiency of practice-based learning. According to Almusawi, medical students can now use IoT-based smart glasses to access medical records, patient data, and surgical procedure guidelines during clinical practice, thus improving the efficiency and accuracy of medical decision-making [46]. In line with these findings, research by Rahmani revealed that augmented reality (AR)-based surgery simulation integrated with IoT devices allows students to practice surgical skills with direct guidance from instructors who can monitor remotely [135]. Dinh also highlighted the benefits of wearable devices in supporting remote supervision by specialist doctors, where patient data is transmitted directly through AR devices to support real-time discussions between doctors and

students without location restrictions [136]. Apart from medicine, wearables also play an important role in engineering and manufacturing, especially in simulation-based training. According to Fu, the application of smart glasses in engineering training can increase learning effectiveness by up to 40%, as it allows direct supervision of procedures and provides instant feedback to users [137]. Dian also suggested that the combination of haptic feedback and IoT sensors in wearable devices further enhances trainees' experience in operating Computer Numerical Control (CNC)-based industrial machines [138]. This is in line with the research of Brown who noted that the aviation and automotive industries have adopted IoT-based wearables to assist pilot and mechanic training through AR-based simulations, allowing trainees to gain real-world experience in engine maintenance and navigation systems [139]. With these innovations, the use of wearables in education is growing to bridge the gap between theory and practice, making learning more effective, safe and efficient [140].

In addition to improving the effectiveness of academic and vocational learning, IoT-based wearables also play an important role in student health monitoring, especially in physical education and sports. According to Tian, the use of fitness bracelets and heart rate sensors allows teachers to monitor students' physical condition in real-time, including pulse rate, oxygen levels in the blood, as well as the intensity of physical activity [141]. With the data collected from these devices, teachers can devise more personalized and safe exercise programs according to students' individual needs. This is reinforced by a study by Olson who found that the use of wearables in physical education has increased students' awareness of the importance of health and fitness by 35%, as they can see their personal health data directly [142]. In further research, Dong highlighted how data collected from wearables can be utilized in the analysis of student fitness trends, allowing teachers to customize exercise programs based on aggregated data from the entire class [143]. In addition, IoT-based wearables have also been used in student mental health monitoring through biometric sensors that are able to detect levels of stress, anxiety, and fatigue during the learning process. Hickey revealed that this monitoring system can provide automatic feedback to students and teachers, thus helping them to better manage academic pressure [144]. In line with this, research by Nagayo showed that an IoT-based stress monitoring system can provide relaxation notifications, breathing exercises, as well as AI-based meditation sessions tailored to students' emotional states [145]. Although IoT-based wearables offer various benefits in improving student learning and health, there are major challenges that need to be considered, namely data security and ethical use. Sam emphasized that these devices collect large amounts of personal information, so educational institutions must implement strict privacy policies, including data encryption and access control to prevent potential misuse of student biometric data [146]. In addition, Jenkins highlights that international regulation of education data security is crucial to ensure that this technology develops in an ethical and responsible manner [147]. With the increasing adoption of IoT-based wearables in education, this technology is expected to continue to innovate and provide a more personalized, secure, and effective learning experience for all students.

3.3.5 Benefits and Challenges of IoT Implementation in Learning

The application of the Internet of Things (IoT) in education is bringing about major changes in the way students and educators access and manage learning. One of the main benefits that IoT offers is increased accessibility to learning materials. According to Shrilekha, with IoT-based devices, students can access teaching materials anytime and anywhere without being limited by physical classrooms [148]. This is especially helpful for those who have limitations in attending classes in person, such as students who live in remote areas or who have physical limitations. In addition, Bhutoria explains that IoT also enables more personalized learning through in-depth data analysis [38]. With systems based on artificial intelligence (AI) and data analytics, IoT can customize learning materials based on each student's learning style. For example, students who better understand concepts through videos or interactive simulations will be given materials in those formats more often, while students who are more comfortable with text will get appropriate readings. Thus, each individual can learn at their own pace and in a way that is most effective for them.

In addition to the benefits in terms of accessibility and personalization of learning, IoT also improves administrative efficiency in educational institutions. Chandrappa mentioned that with an IoT- based system, various administrative processes such as attendance, assessment, and student monitoring can be done automatically and more accurately [149]. For example, the use of RFID sensors or devices that have been developed by Jyothi allows recording student attendance without the need for manual listing by teachers [150]. In addition, Subramanian highlighted that teachers can also utilize IoT to track students' academic progress in real-time, allowing them to provide faster and more targeted guidance [151]. Md Nasir emphasized that this technology also supports increased student engagement in the learning process [152]. With interactive devices such as smartboards, AR (Augmented Reality), and VR (Virtual Reality), learning becomes more interesting and immersive. Students not only read or hear theories, but can also experience hands-on simulations, which can improve their understanding of complex concepts. Furthermore, Bindu showed that IoT also plays a role

in improving security in the school environment [153]. With IoT-based monitoring devices, teachers and parents can keep an eye on students' activities in real-time, ensuring they are in a safe and conducive learning environment. For example, the smart sensors and cameras proposed in the study can help detect suspicious behavior within the school, so that preventive measures can be taken faster to keep students safe.

However, despite its many benefits, the implementation of IoT in education is not free from challenges. One of the biggest challenges is data security. Hasan revealed that with the increasing amount of students' personal information stored in IoT-based systems, the risk of data leakage and information misuse is getting higher [154]. Therefore, educational institutions must ensure that their cybersecurity systems are strong enough to protect student and educator data from the threat of hackers, as described in the research of Masyhur [155]. In addition, Nižetić highlighted that large-scale implementation of IoT requires significant investment in technological infrastructure [23]. Not all schools, especially in less developed areas, have sufficient funds to adopt this technology thoroughly. In addition to cost constraints, Anastasi emphasize that educators also need to receive adequate training in order to effectively use IoT technology in the learning process [50]. Without a good understanding of how IoT devices work, teachers may find it difficult to integrate these technologies into their teaching methods. In addition, Aboubakar noted that limited internet access is also an obstacle in the implementation of IoT, especially in areas that do not have adequate network infrastructure [39]. Without a stable internet connection, IoT-based systems will not be able to function optimally. Another challenge is the potential for over-reliance on technology, which could reduce direct interaction between teachers and students. Education is not only about information transfer, but also building social relationships and interpersonal skills that cannot be completely replaced by technology [156]. Therefore, while IoT brings many benefits to education, it is important for educational institutions to find the right balance in its use, ensuring that it remains a supporting tool that enriches the learning experience, rather than replacing human interaction in the educational process.

3.4. IoT for School Management and Security

The application of the Internet of Things (IoT) in education has brought significant changes to school management systems, especially in the aspects of administrative efficiency, security, and resource management. One of the most common implementations is the IoT-based attendance system, which uses facial recognition, fingerprint scanners, or RFID technology instead of conventional methods such as attendance cards or manual recording [17]. According to El Mrabet, schools that implement this automatic attendance system experience an increase in attendance recording accuracy of up to 98%, while reducing the administrative burden by 40% because the data is directly stored in the school's academic system [157]. This is in line with the findings of Nguyen who stated that IoT technology in attendance systems not only eliminates opportunities for attendance fraud, but also allows real- time tracking of student and teacher attendance [158]. In addition to attendance, IoT is also applied in smart surveillance to improve school security. According to Jain, the use of AI-powered IoT-based surveillance cameras enables early detection of suspicious activities, such as student fights or the presence of strangers in the school environment [159]. Furthermore, research by Parambil showed that the implementation of an AI-IoT-based surveillance system can reduce the rate of security incidents by 60%, as well as speed up the response time of school security officers in dealing with potential threats [160]. In addition, some schools have also integrated IoT-based access control, where automatic doors can only be opened by students, staff, or faculty who have an entry permit that has been registered in the system. In the study of Shashank et al. (2021), the implementation of this access system was shown to improve traffic efficiency within the school environment by up to 30%, especially in schools with a large number of students [161]. This technology not only improves overall security, but also ensures that the school environment remains orderly and under control.

Apart from security and administration, IoT also has a major impact on the management of school resources in a more energy-efficient and sustainable manner. One of the main implementations is smart energy management technology, where smart sensors are used to automatically control lighting, electricity consumption, and HVAC (Heating, Ventilation, and Air Conditioning) systems, based on the presence of individuals in the room or the school's academic schedule [45]. In a study by Al-Obaidi, schools that adopted this technology managed to reduce power consumption by 30% by utilizing automatic light sensors that adjust lighting intensity based on room conditions [47]. This is reinforced by the findings of Rohayani which showed that implementing an IoT-based air conditioning system in a school environment can reduce annual electricity costs by up to 25%, especially in areas with high temperatures that require continuous air conditioning [162]. In addition to energy efficiency, IoT is also utilized in predictive maintenance systems, which allow sensors to detect water leaks, infrastructure damage, and electrical equipment performance before major damage occurs. According to research by Zero, this technology can improve maintenance efficiency by up to 40%, by reducing

response time to unexpected problems [163]. This is also supported by the study of Fernandez which shows that an IoT-based predictive maintenance system can detect potential equipment breakdowns up to 72 hours earlier, extending the life of school devices up to 20% longer compared to conventional methods [164]. With the widespread adoption of IoT in school management, the implementation of automated attendance systems, smart surveillance, and IoT-based energy management will not only improve school operational efficiency, but also create a safer, more efficient, and sustainable learning environment in the digital era.

3.4.1 Automated Time and Attendance Monitoring System

The application of the Internet of Things (IoT) in education has brought revolutionary changes in student attendance management systems, replacing manual record-keeping methods that are often prone to manipulation and administrative errors [165]. With technologies such as facial recognition, fingerprint scanners, and RFID (Radio Frequency Identification) sensors, attendance recording can now be done in real-time without excessive administrative involvement [166]. This is in line with the research of Ula who found that schools that have implemented an IoT-based attendance system experienced an increase in recording accuracy of up to 98% and a 40% reduction in administrative burden [167]. Attendance data that is directly integrated into the school's academic system not only reduces the workload of education personnel but also increases transparency in managing student attendance. In Inayah addition to administrative efficiency, the utilization of IoT-based Artificial Intelligence (AI) allows predictive analysis of attendance trends, providing insights to education personnel in identifying students who are at risk of academic problems due to repeated absences [168]. Teachers and school authorities can take early intervention measures before a student's absenteeism negatively impacts his or her academic performance. The study conducted by Mamatnabiyev also highlights how IoT improves the security of the school environment by integrating an attendance system with automatic access control [169]. This system allows only students who have registered with the attendance system to enter the school premises, thereby reducing incidents of intrusion and improving security control. In addition, with automatic notifications sent to parents when their children are absent without authorization, transparency between schools and guardians is increased, allowing them to take immediate action in the event of unexcused absences [170].

In addition to improving efficiency in the attendance system, IoT has also brought innovation in student transportation monitoring. Some schools have integrated IoT-based GPS to enable real-time tracking of school bus locations by school authorities and parents. According to research conducted by Karolemeas, the application of this technology can increase student travel safety by 35%, because the system can provide estimated arrival time, optimize travel paths based on traffic conditions, and send automatic arrival notifications [171]. Another study by Alfaifi showed that schools that implemented an IoT- based GPS system experienced a decrease in student tardiness by 28%, because the system helped manage transportation schedules more efficiently [31]. In addition to transportation, monitoring students in the school environment is also increasingly accurate with IoT sensors, which can detect the presence of students in various locations such as classrooms, laboratories, and libraries [172]. With this system, schools can keep an eye on students' mobility to ensure they are in the places that match their academic schedules. Ojo noted that schools that implemented IoT in their attendance monitoring system saw a 42% decrease in truancy cases, thanks to stricter supervision and early intervention from education personnel [170]. With the widespread adoption of IoT in automated attendance systems, student monitoring, and GPS integration in school transportation, the world of education is moving towards a more transparent, efficient, and secure management system. As the technology evolves, it is predicted that IoT will be increasingly integrated with adaptive learning systems, enabling a more personalized and data-driven learning experience. Thus, IoT-based innovations not only improve education management, but also create a more conducive and future-oriented learning environment.

3.4.2 School Security Monitoring with IoT

Security in educational environments is one of the fundamental aspects that should be prioritized, especially with the increasing challenges in school security management. The Internet of Things (IoT) has brought innovative solutions in school monitoring, enabling a more automated, responsive and real-time data-driven security system [173]. The application of IoT-based surveillance camera technology supported by artificial intelligence (AI) has enabled schools to detect suspicious activities and recognize the faces of individuals entering and exiting the school environment, as well as send automatic alerts to security personnel if a potential threat is detected [174]. Gilbert assert that this technology increases monitoring efficiency by 50% compared to conventional methods [175]. In addition, schools are starting to adopt AI-based analytics technology that enables security systems to detect unusual crowds, aggressive movements, or indications of dangerous actions within the school area [176]. The implementation of AI in school security systems is also supported by Al Ghazo, who emphasize that these technologies not only enable early detection of security

threats but also help coordinate emergency responses more efficiently through automated alert systems [41]. Furthermore, some schools have integrated IoT drone-based surveillance that is capable of monitoring large areas such as entrance gates, parking areas, as well as student play zones. Farag noted that this method is more effective than conventional surveillance, especially in school environments that have large areas and require optimal real- time monitoring [177].

In addition to video-based monitoring technology, schools have also implemented IoT-based access systems to improve the security of certain areas. IoT-based facial recognition technology and smart access cards allow schools to control who can enter a laboratory, server room, library, or principal's office, ensuring that only authorized individuals can access those areas [178]. Ann Roseela found that schools that implemented dual biometric authentication experienced a 42% reduction in intrusion incidents [51]. In addition, the use of IoT-based motion and sound sensors has become increasingly popular in detecting potential threats within the school environment, such as fights between students, the sound of breaking glass, or suspicious activities outside of school operating hours [179]. Shafiq asserted that schools that adopted IoT sensor-based monitoring systems experienced a 35% decrease in violent incidents, as this technology enables early detection of threats and accelerates intervention by security personnel [180]. Furthermore, some schools have integrated IoT-based evacuation systems that use smoke sensors and gas detectors to automatically open emergency exits and guide students towards safe evacuation routes, enabling rapid response in emergency situations such as fires or gas leaks [181]. The use of these systems has been shown to improve safety in emergency situations, especially in schools with large numbers of students and complex infrastructure.

While IoT provides many benefits to school security, a major challenge in its implementation is the protection of data and privacy of students and education personnel. With the increasing use of facial recognition, biometrics, and AI-based monitoring, there are concerns about how students' and staff's personal data is managed and stored securely [182]. Chidukwani revealed that only 58% of schools have implemented high-level encryption policies in their IoT-based security systems, while the rest are still vulnerable to cyberattacks [183]. This shows that although IoT-based security technologies provide better physical protection, there are still security gaps that can be exploited by irresponsible parties. To address this challenge, schools should adopt stricter cybersecurity protocols, including the use of data encryption, multi- factor authentication, and periodic audits of their security systems [34]. In addition, strict regulations regarding the use of biometric data in educational settings should be clarified so as not to violate students' privacy rights. Amo emphasize that the combination of advanced surveillance technology with strict data protection policies will help create a more secure and trustworthy learning environment [49]. Therefore, for the implementation of IoT in the school environment to run optimally, schools need to consider technological and regulatory aspects simultaneously. With this strategy, it is expected that the educational environment can remain safe, efficient, and comfortable for students and educators in this digital era.

3.4.3 School Energy and Facilities Management

The development of the Internet of Things (IoT) in school energy and facilities management has brought about significant changes in resource management, both in terms of energy efficiency, reduced operational costs, and environmental sustainability. According to Muthubalaji, the implementation of IoT sensor-based systems in the school environment enables smarter management of energy consumption, especially in controlling lighting, room temperature, and other electrical devices based on the presence of individuals in the room [184]. The system works automatically, so that when a classroom or laboratory is not in use, the lights will be turned off, the air conditioning temperature adjusted, and other electronic devices will be disabled to save energy without requiring manual intervention [185]. The effectiveness of this technology has been proven in a study by Mahmoud, where schools that implemented an IoT-based smart energy management system were able to reduce electricity consumption by up to 30%, having a direct impact on reducing operational costs and increasing energy efficiency [186]. Along the same lines, recent research by Challa highlighted how machine learning- based IoT systems can analyze energy consumption patterns and automatically adjust the required power based on actual needs in schools, so that energy efficiency can be continuously improved without reducing user comfort [187]. Apart from power efficiency, IoT systems also have a significant impact on environmental sustainability. In the study of Benhamaid, it was found that schools that adopt IoT-based energy management systems can reduce carbon emissions by up to 20% per year, as the reduction in energy consumption contributes directly to the decrease in the carbon footprint generated [188]. This is further reinforced by the findings of Gautam which showed that an IoT-based energy management system integrated with artificial intelligence (AI) technology can actively detect energy waste and make automatic adjustments, reducing dependence on unnecessary excess power usage [189]. With this technology

in place, schools are not only able to save significantly on operational budgets but also support global initiatives to reduce energy consumption and improve environmental sustainability.

In addition to energy efficiency, IoT also plays an important role in the management of school facilities, especially in detecting potential infrastructure problems before major damage occurs. The utilization of IoT sensors in plumbing systems, for example, allows schools to detect water leaks early so that repairs can be made immediately without unnecessary water wastage. According to research by Guezouli, schools that implemented an IoT-based water monitoring system experienced a reduction in water consumption of up to 25% because the system can automatically shut off water flow when a leak is detected, avoiding waste due to piping damage that often goes undetected manually [190]. In addition, IoT-assisted predictive maintenance has become an effective solution in keeping school facilities in optimal condition. IoT sensors allow schools to detect changes in usage patterns and flag potential malfunctions in electrical devices, HVAC (Heating, Ventilation, and Air Conditioning) systems, and laboratory equipment before major damage occurs [191]. In the research of Elkateb, it was found that a predictive analytics-based IoT system can save up to 35% on facility maintenance costs by enabling early intervention before equipment fails completely [192]. With this technology, schools can plan maintenance based on real-time data, ensuring that all facilities operate properly without having to rely on time- and labor- consuming manual inspections. However, while the benefits of implementing IoT in school energy and facilities management are immense, the main challenges to be faced are the initial cost of investment as well as data protection in IoT-based systems [193]. Installation of sensor infrastructure, monitoring software, and integration with school management systems are costly. In addition, data security is a serious concern because cloud-based systems can be vulnerable to cyberattacks if not equipped with adequate security systems. Rekeraho revealed that only about 60% of schools that have adopted IoT use strict cybersecurity standards, while the rest still face high risks related to data security [194]. Therefore, schools need to implement additional security measures such as data encryption, multi-factor authentication, and periodic audits to ensure that IoT systems remain safe from cyber threats [186]. Despite these challenges, the long-term benefits of adopting this technology still far outweigh the obstacles. With the development of technology and the widespread adoption of IoT in education, schools of the future can manage their facilities more intelligently, efficiently, and environmentally friendly [193]. In addition to providing operational budget savings, the implementation of IoT is also part of a sustainability initiative that can improve the comfort and quality of the learning environment for students and teaching staff [8].

3.4.4 Smart Emergency Safety and Evacuation System

School safety in emergency situations, such as fires, earthquakes, or other threats, is a major concern for educational institutions around the world. The Internet of Things (IoT) has brought about a revolution in emergency security systems by enabling sensor-based early detection that works in real-time. According to Mohsin, this technology allows schools to install various sensors, such as temperature sensors, smoke, harmful gases, and vibration sensors that are able to detect potential dangers early on [195]. In addition, Sari revealed that schools that adopted IoT in their security systems experienced a 38% increase in early detection efficiency compared to schools that still rely on conventional methods [196]. These detection systems not only identify threats, but also automatically send alerts to school officials, fire departments, and emergency response teams. Hassin explained that with IoT-based systems, responses to fires can occur faster because the system is able to connect various related parties without the need for human intervention [197]. This finding is reinforced by the research of Zhang, who found that schools that implemented IoT-based fire detection systems experienced a 40% reduction in response time, thanks to automatic notifications sent directly to the fire department and school authorities [198]. On the other hand, Tariq also noted that IoT-based early warning systems have helped reduce the risk of fatalities by 25%, especially with the implementation of artificial intelligence (AI) that is able to analyze fire patterns more accurately [199]. Apart from fires, IoT has also proven effective in detecting earthquakes earlier. IoT-based seismic sensors can identify initial tremors before major shaking occurs, giving students and educators the opportunity to seek shelter immediately. Al-Nabhan explain that these systems can also be configured to disable electrical power sources to reduce additional risks, such as short circuits or fires secondary to the earthquake [36]. In addition, recent research conducted by Akhavan found that IoT- based earthquake detection systems can increase the effectiveness of evacuation procedures by up to 30%, especially in earthquake-prone areas [40]. With this technology, schools can ensure that disaster preparedness is improved, while minimizing the negative impacts that may occur.

In addition to early detection systems, IoT also plays an important role in smart evacuation systems. Zhang highlighted that this system works by utilizing IoT sensor-based digital mapping as well as artificial intelligence (AI)-based voice guidance that provides evacuation instructions automatically according to the detected hazard location [198]. Research conducted by Chen Siyao showed that the implementation of an IoT-based evacuation system can reduce evacuation time by 35% because this system is able to update safe paths

based on the current conditions in the school building during emergency situations [200]. This is in line with the findings of He, who showed that the integration of IoT in evacuation routes allows for dynamic adjustments to exit routes, thereby reducing the possibility of congestion during an evacuation [201]. Some schools have also adopted smart emergency lighting systems integrated with IoT. These systems are capable of providing automatic lighting paths along evacuation routes in the event of a main power failure due to a disaster. However, while the benefits of IoT in school safety are immense, implementation challenges remain. He noted that only 50% of schools have sufficient network infrastructure to support the full implementation of IoT-based security systems [201]. Meanwhile, the remaining schools still rely on conventional alarm systems that are not always responsive to emergencies. In addition to infrastructure constraints, Jarašūnienė highlighted that the initial installation cost is still a major obstacle for many educational institutions, especially in developing countries [202]. Nonetheless, the long-term benefits of IoT security systems still far outweigh the initial investment costs. According to a recent study by Kamel, schools that implemented IoT in their security systems experienced a 45% increase in safety thanks to more accurate early detection and more effective evacuation systems [90]. As technology continues to evolve and there is support from various parties, it is expected that more schools can adopt this system to significantly improve the safety of students and teaching staff.

3.4.5 Advantages and Challenges in IoT-based School Management

The application of the Internet of Things (IoT) in education has become one of the major innovations in improving the efficiency and effectiveness of school management. With IoT, various administrative tasks can be automated, reducing the burden on educators and increasing operational efficiency. Suhandi, the implementation of IoT in a sensor-based attendance recording system has reduced administrative errors by 35%, allowing schools to focus more on learning development [203]. In addition, IoT-based surveillance systems also provide significant benefits in improving school security. Gudikandhula found that the implementation of an artificial intelligence-based IoT face detection system and surveillance cameras can reduce school security incidents by 40% [204]. This security is strengthened by the presence of monitoring sensors that can detect emergencies, such as fires and earthquakes. According to research conducted by Al-Hady, schools that have integrated IoT sensors in the fire alarm system experienced a 50% increase in evacuation response, enabling faster preventive action and reducing the risk of casualties [43]. Not only that, the utilization of IoT in energy efficiency is also proven to be able to reduce school operational costs. Jebur mentioned that the use of an IoT- based automatic lighting and air conditioning system has reduced the school's electricity consumption by 30%. This efficiency is very helpful for schools in allocating budgets for other needs, such as curriculum development and improving learning facilities [205]. In addition to operational aspects, IoT also has a positive impact on student health monitoring. Semary explained that IoT sensors installed on students with special needs allow real-time monitoring of heart rate and oxygen levels in the blood [206]. This helps medical personnel at school to take immediate action in the event of an emergency, so that student health can be better maintained.

Despite its many benefits, the implementation of IoT in education also faces a number of challenges that need to be considered. One of the main challenges is data security and privacy. With IoT systems continuously collecting and storing data from students as well as school staff, the risk of data leakage is a serious concern. Derbas state that without a strong encryption system, personal data collected by IoT devices can be utilized by irresponsible parties for various purposes, including identity theft and information misuse. In addition to data security, another obstacle that is often faced is the high cost of implementation [207]. Mustafa revealed that IoT infrastructure in schools requires large investments, especially for hardware, software, and educator training [208]. This is a big challenge for schools that have limited budgets, especially in developing countries. Another challenge is the dependence on a stable internet network. Terzieva emphasized that IoT systems can only work optimally if supported by a fast and reliable internet connection [8]. Unfortunately, many schools in remote areas still experience difficulties in accessing adequate internet, making the implementation of IoT less effective. In addition, the readiness factor of educators in operating the IoT system is also a challenge. Timotheou emphasized that without sufficient training, educators and school staff may have difficulty in adopting this technology effectively [209]. Therefore, training and capacity building for teachers and school administrators are very important in supporting the successful implementation of IoT in education. With various challenges, the implementation of IoT in education remains a major necessity in facing the digital era. Although there are obstacles in its implementation, various solutions can be applied, such as strengthening data security systems, providing more affordable infrastructure, and training educators. Thus, this technology not only improves the efficiency of school operations, but also creates a safer, more comfortable and conducive learning environment for students and educators.

3.5 Advantages and Challenges of IoT in Education

3.5.1 Advantages of IoT in Education

The application of the Internet of Things (IoT) in education provides significant benefits in improving the quality of learning, school management, and administrative efficiency. IoT technology allows schools and educational institutions to develop a more interactive and data-driven learning environment, thus being able to respond to student needs more adaptively. According to Pogoh, the utilization of IoT devices in learning improves the interaction between teachers and students through real-time data-driven systems that can be tailored to individual needs [210]. Devices such as smartboards, smart sensors, and wearable technology make the learning process more dynamic and personalized, allowing teachers to monitor students' progress directly and adjust teaching methods accordingly. Shi found that the use of IoT in the classroom increased student engagement by 40% due to a more interactive and data-driven learning experience [211]. In addition to learning, IoT also supports school management efficiency, such as the automation of attendance recording systems, security monitoring through IoT-based CCTV, and more efficient energy management. Bhagyaveni reported that the implementation of IoT in schools can reduce energy consumption by 30% by automating lighting and air conditioning [212]. Another advantage is the optimization of big data analysis, allowing schools to make strategic decisions based on learning trends and student behavior. Moraiti also highlighted that the accessibility of IoT-based learning increased the participation of students with special needs by 35%. With IoT integration, access to digital learning resources becomes wider and more flexible, supporting distance learning and inclusive education [213]. Here are some of the key advantages of IoT implementation in education:

3.5.1.1. Improving Accessibility and Inclusivity of Learning

The Internet of Things (IoT) has revolutionized education by allowing students to access learning materials flexibly, anytime and anywhere, through cloud-based platforms and internet-connected smart devices. This is especially beneficial for students living in remote areas, as they can still participate in online learning without being hindered by geographical limitations [214]. According to a recent study by Bajaj, the use of IoT in education also enables the integration of artificial intelligence-based technologies to customize learning materials according to the needs and individual abilities of students [215]. This supports the implementation of hybrid learning models, where students can choose to attend classes in person or connect through digital connections without losing the optimal learning experience. The study conducted by Adhicandra shows that the use of IoT devices in a hybrid classroom can increase interactivity as well as student engagement in the learning process [30]. In addition, IoT also plays an important role in supporting educational inclusivity, especially for students with special needs. IoT-based technologies such as text-to-speech and speech-to-text allow them to access course materials more easily through voice-to-text conversion that can be used in note-taking or comprehension. Thus, the integration of IoT in education not only improves accessibility but also creates a learning environment that is more adaptive and responsive to students' needs.

3.5.1.2. Personalized Learning Based on Data and AI

The Internet of Things (IoT) plays an important role in collecting and analyzing data regarding students' learning patterns, academic performance, as well as their level of engagement in the classroom. With sensor technology and smart devices integrated in digital education systems, teachers and educational institutions can monitor students' progress in real-time, enabling faster and more targeted interventions [216]. In addition, artificial intelligence (AI) systems connected to IoT are not only able to process large amounts of data but also provide recommendations for the most effective learning methods for each student based on analysis of their learning habits and level of understanding. According to research conducted by Das, adaptive learning platforms supported by IoT can automatically adjust curriculum and teaching materials, thus creating a more personalized and effective learning experience [217]. This technology allows students to receive material that suits their pace and learning style, thereby reducing boredom levels and improving retention of understanding. Furthermore, the use of IoT in education also enables gamification-based learning systems, where interactive elements can be added to increase student engagement [218]. Thus, the application of IoT in learning not only improves the efficiency of the education system but also contributes to creating a more adaptive, innovative, and student-centered learning experience.

3.5.1.3. School Administration Efficiency and Resource Management

The Internet of Things (IoT) has brought about a revolution in the automation of various administrative tasks in the education sector, reducing the workload of teachers and administrative staff and improving the operational efficiency of schools and educational institutions. One of the key implementations is a facial recognition-based automated attendance system that enables accurate recording of student attendance

without manual intervention, thereby reducing the possibility of recording errors and fraud [66]. In addition, IoT supports digital curriculum management, enabling automatic updating of teaching materials and customization of content based on student development. According to research conducted by Zhao, IoT technology also enables the monitoring of student engagement in online classes through data analysis of their activities, including attendance duration, interaction with materials, and responses to assigned tasks [219]. Furthermore, IoT plays a role in class schedule management by adjusting time allocation based on analysis of student attendance and academic needs, while optimizing the use of classrooms and other educational resources in real-time. The study by McCarthy shows that utilizing IoT in school management can increase operational efficiency by up to 40% by reducing administrative errors and speeding up the decision-making process [220]. Thus, the integration of IoT in education administration not only improves the effectiveness of school management but also allows educators to focus more on developing more innovative and quality learning strategies.

3.5.1.4. School Safety and Environmental Monitoring

The application of the Internet of Things (IoT) in school security systems has brought significant innovations in the monitoring and protection of educational environments. With integrated sensor technology and smart CCTV, schools can conduct real-time surveillance and detect potential security threats faster, including intrusions, fights, or other emergency events [221]. According to research conducted by Lulla, the application of IoT in school security systems has been shown to improve incident response by up to 50% faster than conventional systems [222]. In addition to AI-based video monitoring, IoT also enables access control to certain areas in schools through the use of smart cards and biometric recognition technology, so that only authorized individuals can enter classrooms, laboratories, or other sensitive facilities. This technology not only reduces the risk of security breaches but also helps create a safer and more conducive learning environment. Furthermore, IoT-based remote monitoring allows school authorities as well as parents to monitor students' movements while in the school environment in real-time through mobile applications or cloud-based dashboards [223]. With the integration of these technologies, school security can be significantly improved, providing a sense of security for students, teachers, and the entire educational community, and ensuring that learning takes place in a more protected and comfortable environment.

3.5.1.5. Energy Management and School Sustainability

The application of Internet of Things (IoT) sensors in school facility management has brought significant changes in energy efficiency and environmental sustainability. With sensor technology capable of detecting the presence of users in the classroom, lighting and air-conditioning automation systems can be activated or deactivated as needed, significantly reducing energy consumption. A study conducted by Qu showed that schools that implemented this system experienced a 30% reduction in energy consumption, which has a direct impact on operational cost efficiency [224]. In addition, IoT also enables real-time monitoring of electricity usage, allowing schools to analyze consumption patterns and optimize power distribution to prevent wastage. Not only in the energy aspect, IoT systems also play a role in water and waste management, where IoT-based sensors can detect water leaks, measure consumption levels, and provide early warnings in case of resource wastage [205]. With this technology, schools can implement more effective green practices, such as water recycling and data-driven waste management, supporting sustainability initiatives. According to recent research by Azar, the use of IoT in education facility management not only reduces environmental impact but also provides a healthier and more comfortable learning experience for students and educators [225].

3.5.2 Challenges of IoT Implementation in Education

3.5.2.1. Data Security, Privacy and Ethical Regulation

The application of the Internet of Things (IoT) in education brings great benefits in the collection and analysis of student data, but also presents major challenges regarding information security. IoT collects and stores a variety of students' personal data, including their academic records, learning habits, as well as their digital interactions within the learning system. Therefore, data protection should be a top priority to prevent the risk of information leakage and misuse by irresponsible parties [226]. According to research conducted by Naik, the implementation of strong encryption systems and multi- factor authentication can significantly reduce the risk of unauthorized access to sensitive information [227]. Blockchain technology is also starting to be applied in IoT-based education systems to improve the transparency and security of student data, ensuring that academic information can only be accessed by authorized parties. In addition to technical aspects, clear regulations regarding data protection in education are needed so that institutions can manage student

information safely and in accordance with applicable legal standards [228]. Without strict regulations, the potential for data misuse will increase, especially in this increasingly complex digital era. With a combination of advanced security technology and clear regulations, the application of IoT in education can still provide optimal benefits without compromising the privacy and security of student data and educators.

3.5.2.2. Implementation Costs and Technology Infrastructure

The application of the Internet of Things (IoT) in education offers a wide range of benefits, but also faces a major challenge, namely a large initial investment. The required infrastructure includes high-speed internet networks, IoT devices such as sensors and smart devices, as well as supporting systems such as cloud servers and analytics software to manage and analyze learning data. For schools with limited budgets, the high implementation cost is a major obstacle in adopting this technology thoroughly [229]. According to a study conducted by Sultana, many educational institutions in developing countries still experience difficulties in providing adequate infrastructure to support IoT, thus requiring support from various parties [230]. Therefore, collaboration between the government, technology industry, and educational institutions is essential to ensure wider access to IoT technologies. Funding schemes such as subsidies, technology grants, and partnership programs can be a solution for schools in need. Some countries have developed incentive policies for educational institutions that adopt IoT to improve the quality of learning [231]. With the right support, the application of IoT in education can be more inclusive, ensuring that all schools, including those in resource-constrained areas, can benefit from digital transformation in the learning process.

3.5.2.3. Internet Connection and Network Stability

The performance of the Internet of Things (IoT) in education is highly dependent on the quality of a stable and high-speed internet connection. Schools located in areas with limited or unstable internet access may experience obstacles in optimally operating IoT-based systems, such as delays in data transmission, interruptions in real-time monitoring, and difficulties in accessing digital learning resources [232]. According to a study conducted by Clarin, the low network quality in some regions hinders the application of IoT in education, especially in the implementation of smart classrooms and cloud- based learning systems [233]. Therefore, improving network infrastructure is a crucial step to support digital transformation in education. The government and technology service providers need to collaborate in providing wider and more stable connectivity, including the development of 5G networks and the expansion of broadband access in remote areas. Another alternative to overcome connectivity limitations is the use of edge computing, where data processing is done locally on IoT devices before being sent to the cloud. This technology allows IoT systems to continue operating even if the internet connection is lost, thereby improving system efficiency and resilience [234]. With the combination of network infrastructure improvements and the adoption of edge computing technology, schools can be more optimized in implementing IoT without being constrained by connectivity issues.

3.5.2.4. Training and Adaptation of Educators

For the effective implementation of the Internet of Things (IoT) in education, teachers and school staff need to receive adequate training in operating and managing IoT-based devices and systems. Lack of understanding of this technology can hinder adoption and reduce the effectiveness of IoT in supporting the learning process, especially in the utilization of smart classroom systems, student data monitoring, and IoT-based administrative management [235]. According to research conducted by Ghasim, schools that provide special training for educators in the use of IoT technology experience an increase in teaching efficiency of up to 40% because teachers are more confident in integrating smart devices into learning [4]. Therefore, digital literacy programs should be part of the educator training curriculum, with approaches that cover basic IoT theory, device usage, IoT-based educational data analysis, and data security. In addition, hands-on IoT technology training workshops need to be held regularly so that educators can keep abreast of technological developments and apply them effectively in the classroom [236]. With comprehensive and continuous training, teachers and school staff can be better prepared to face the challenges of digital transformation in education, ensuring that IoT technology can be optimally utilized to improve the quality of learning and school management.

3.5.3. Solutions and Strategies for IoT Implementation in Education

The application of Internet of Things (IoT) technology in education offers significant benefits, ranging from administrative efficiency, interactive learning, to more accurate student monitoring. However, a key challenge to overcome is data security, given the growing number of interconnected IoT devices that collect data in real-time [237]. One of the key solutions is the adoption of high-level encryption technology to ensure

the security of student and staff information from cyberattacks [238]. In addition, the implementation of strict privacy policies is an essential step in limiting access to data to authorized parties. Wambua recommended the implementation of double authentication and advanced firewalls as additional protection for IoT systems in education. Other efforts include segmenting IoT networks using Virtual LANs (VLANs) and Zero Trust Architecture (ZTA) to limit device access and reduce the risk of compromise [239]. Artificial Intelligence (AI) can also be utilized in Intrusion Detection Systems (IDS) to detect anomalous patterns in data traffic and prevent attacks before they occur. In addition, blockchain can be used in IoT data management to ensure the integrity and security of stored information. Firmware updates and cybersecurity training for educators and students are also crucial aspects in reducing the risk of exploitation. By implementing these strategies, educational institutions can optimize the potential of IoT while ensuring maximum data security.

3.5.3.1. IoT Implementation Solution in Education

The application of the Internet of Things (IoT) in education has great potential to improve learning effectiveness, administrative efficiency, and educational accessibility in various regions. However, to optimize the implementation of IoT in the education sector, there are three main solutions that need to be considered, namely improving data security, investing in infrastructure, and strengthening the skills of educators. Data security is a crucial aspect in the implementation of IoT because every connected device has the potential to become a loophole for sensitive information leakage, both related to student personal data and institution academic documents. For this reason, the implementation of layered security systems, such as high-level data encryption and multifactor authentication, is a necessary step to minimize the risk of cyber attacks. A study by Kohad shows that 78% of educational institutions that have implemented IoT-based security systems experienced a significantly reduced risk of data leakage after adopting encryption and layered authentication technologies [240]. In other words, efforts to improve the protection of IoT-connected systems will have a major impact on maintaining the integrity of educational data and building trust for stakeholders in the digital education system. In addition to technical protection, awareness and education related to cybersecurity for users, especially educators and students, are also needed to reduce the risk of attacks originating from human error. Many cases of data leakage in educational institutions have occurred due to users' lack of understanding in managing access to IoT-based devices and systems. Therefore, a security policy that involves regular training, role-based access control, and active monitoring of the institution's network should be a priority for schools and universities that want to adopt IoT technology safely and sustainably.

In addition to the security aspect, another factor that plays an important role in supporting the implementation of IoT in education is infrastructure readiness, especially a stable and fast internet network. In many cases, schools in remote areas face major challenges in accessing high-quality internet, limiting the optimal application of IoT technology. According to research by Hanum, investment in internet network upgrades in schools can accelerate IoT adoption by 65% within five years [66]. This shows that without adequate infrastructure, IoT in education cannot develop optimally. The government and educational institutions need to work together to ensure that every school, especially in areas with limited internet access, gets adequate technology support. One solution that can be implemented is the utilization of satellite-based networks or 5G technology to accelerate access to IoT-based digital services. In addition, increasing the number of supporting devices, such as smart sensors and interactive whiteboards, can help accelerate digital transformation in learning. However, the availability of good infrastructure alone is not enough without the readiness of educators to adopt these technologies. A study by shows that teachers' lack of understanding of IoT technology is a major hindering factor in the implementation of IoT in learning. Therefore, intensive training programs must be provided to educators so that they have the competence to manage and utilize IoT in the classroom. Alvendri found that 85% of teachers who participated in hands-on training were able to integrate IoT in learning better than those who only received theoretical training [48]. In other words, a hands-on approach allows educators to understand how IoT works more deeply and apply it in real learning scenarios. Once educators have sufficient skills in using IoT, they can design more innovative, interactive learning experiences that increase student engagement. With the combination of strong security, good infrastructure, and competent educators, IoT can be a key pillar in creating a more modern, inclusive, and responsive education ecosystem for the digital age.

3.4.3.2. IoT Implementation Strategy in Education

In addition to the aforementioned solutions, the implementation strategy of the Internet of Things (IoT) in education should also include clear regulations and close collaboration between educational institutions and the technology industry. Strict regulations are needed to ensure that the use of IoT remains in

accordance with applicable ethical and legal principles, especially related to data protection and students' privacy rights. A study conducted by Isman showed that strong policies in the implementation of IoT in the school environment can increase public trust by 60% [241]. This proves that good regulations not only ensure data security but also increase public acceptance of technological innovation in education. In the implementation of IoT, many aspects must be strictly regulated, including how student data is collected, used, and stored by schools or third parties who cooperate in managing IoT systems. Clarity on access restrictions to data is also very important to prevent misuse of personal information that can harm students. One of the biggest challenges in this regulation is ensuring that IoT devices used in schools comply with global security standards, so that there are no loopholes for cyberattacks or leakage of sensitive information. In addition, the government and educational institutions need to design transparent policies that ensure that the technology implemented is aligned with students' right to a safe and inclusive education. Without clear regulations, there is a risk that the use of IoT in schools could actually become an excessive monitoring tool that interferes with academic freedom and reduces students' comfort in the learning process.

In addition to strict regulations, IoT implementation strategies in education should also include close collaboration between schools and the tech industry. This strategic partnership is crucial given the complexity of IoT technology, which requires adequate infrastructure, compatible devices, and ongoing technical support. According to Moraes, educational institutions that collaborate with technology companies tend to get more affordable IoT solutions that suit their educational needs. This shows that partnerships between the education sector and the technology industry are not only beneficial in terms of access to IoT devices and systems but also in terms of reducing costs and increasing the effectiveness of implementing these technologies in schools [242]. In addition, this collaboration allows schools to receive training from technology experts so that educators can better understand how to integrate IoT in learning effectively. One concrete example of the success of this collaboration is the implementation of smart classrooms in several schools in collaboration with leading IoT solution providers. With collaboration, schools can utilize various IoT-based devices such as smart whiteboards, attendance sensors, and automated classroom management systems that help improve learning efficiency. Furthermore, this partnership can also create an innovation ecosystem that allows schools to develop technology-based curriculum, introduce STEM-based programs (Science, Technology, Engineering, and Mathematics), and provide greater access for students to understand future technologies. However, for this collaboration to work optimally, there needs to be a monitoring mechanism from an independent party to ensure that the relationship between schools and industry remains based on the principle of transparency and does not trigger excessive dependence on products or services from one particular company.

With strict regulations and effective industry collaboration, IoT has great potential to revolutionize the education system as a whole. However, successful implementation depends not only on these two factors but also on infrastructure readiness, educator training, and continuous investment in technology development that supports IoT-based learning. Recent research by Mircea shows that schools that partner with the technology industry have a 40% higher IoT adoption rate than schools without such collaboration [6]. This suggests that strong partnerships play an important role in accelerating the integration of IoT in the education system. However, it should be noted that even if technology adoption increases, its effectiveness still depends on the readiness of educators to utilize this technology optimally. Therefore, schools need to invest in training and professional development programs for teachers so that they are not only capable of using IoT technologies but can also teach students how to utilize them to enhance the learning experience. In addition, there needs to be a continuous evaluation system that ensures that the use of IoT truly benefits learners and is not just a technology trend without significant impact. With a combination of strict data security, adequate infrastructure, educator training, structured regulations, and collaboration with industry, IoT implementation can run optimally and have a positive impact on education in the future. Through the right strategy, IoT can not only improve operational efficiency in schools but also open up new opportunities in more interactive learning methods, personalization of learning based on real-time data, and enhancement of a more engaging learning experience for students in the digital era.

4. CONCLUSION

The application of the Internet of Things (IoT) in education has brought about a substantial transformation in the learning process and school management, creating an ecosystem that is more interactive, efficient, and data-driven. The use of devices such as digital whiteboards, smart projectors, and wearable devices enables the personalization of teaching materials based on real-time data analysis, which has been proven to significantly increase student engagement. On the managerial side, this technology encourages the automation of administrative systems, such as RFID-based attendance and facial recognition, student monitoring via GPS, and increased security through artificial intelligence-based CCTV, which collectively

contribute to increasing school security by up to 60%. In addition, the IoT-based energy management system enables school electricity savings of up to 30% per year, as well as predictive maintenance that can reduce facility maintenance costs by up to 35%. However, behind this great potential, this study highlights major unresolved challenges, such as data security risks, high implementation costs, and infrastructure limitations in non-urban areas. The risk of data leakage and cyber attacks is a real concern that requires educational institutions to adopt layered security systems based on encryption and dual authentication. Therefore, this study emphasizes that the adoption of IoT in the education sector needs to be balanced with the strengthening of data security regulations and increasing the capacity of teachers through regular technology training. To broaden contextual understanding, further studies are recommended to explore the real implementation of IoT in rural schools using a case study approach, to identify effectiveness, field challenges, and replication potential. With a strategic and inclusive approach, IoT can be the main driver of sustainable digital education transformation that is adaptive to the challenges of the modern era.

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