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Integrating IoT-Based Learning Media to Enhance Science Literacy and 21st-Century Skills in Elementary Education: A Systematic Literature Review

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Abstract

This study addresses the challenge of organic waste management arising from the Makan Bergizi Gratis (MBG) program in elementary schools, where inadequate waste processing systems limit both environmental sustainability and contextual learning opportunities. To respond to this issue, the study aims to examine the role of Internet of Things (IoT)-based learning media in enhancing elementary school students' science literacy and 21st-century skills, as well as to identify its pedagogical benefits and implementation constraints. A Systematic Literature Review (SLR) was conducted by screening 200 articles published between 2021 and 2026 using Google Scholar through the Publish or Perish application. Based on predefined inclusion criteria focusing on IoT-based STEM learning, elementary education contexts, and learning outcomes related to literacy and 21st-century skills 18 articles were identified as relevant, and 9 peer-reviewed studies were selected for detailed analysis. The findings indicate that integrating IoT into organic waste management enhances student engagement through observation, real-time data collection, and analysis. Science literacy improved through contextual understanding of concepts, while 21st-century skills, particularly critical thinking, creativity, and collaboration, were fostered through problem-based and data-driven learning. However, the effectiveness of IoT-based learning media is influenced by infrastructure readiness and teachers' technological competence. This review highlights IoT-based learning media as a strategic and sustainable innovation for supporting contextual science education in elementary schools.

Keywords: 21st Century Skills, IoT Learning Media, Science Literacy, STEM

Integrasi Media Pembelajaran Berbasis IoT untuk Meningkatkan Literasi Sains dan Keterampilan Abad ke-21 pada Pendidikan Sekolah Dasar: Systematic Literature Review

Abstrak

Penelitian ini membahas tantangan pengelolaan sampah organik yang muncul dari program Makan Bergizi Gratis (MBG) di sekolah dasar, di mana keterbatasan sistem pengolahan sampah menghambat keberlanjutan lingkungan sekaligus pembelajaran kontekstual. Penelitian ini bertujuan untuk mengkaji peran media pembelajaran berbasis Internet of Things (IoT) dalam meningkatkan literasi sains dan keterampilan abad ke-21 siswa sekolah dasar, serta mengidentifikasi manfaat pedagogis dan kendala implementasinya. Metode yang digunakan adalah Systematic Literature Review (SLR) dengan menelaah 200 artikel yang dipublikasikan pada periode 2021–2026 melalui Google Scholar menggunakan aplikasi Publish or Perish. Berdasarkan kriteria inklusi yang telah ditetapkan meliputi pembelajaran STEM berbasis IoT, konteks pendidikan sekolah dasar, serta luaran literasi dan keterampilan abad ke-21 teridentifikasi 18 artikel relevan, dan 9 artikel bereputasi dipilih untuk dianalisis secara mendalam. Hasil kajian menunjukkan bahwa integrasi IoT dalam pembelajaran pengelolaan sampah organik

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meningkatkan keterlibatan aktif siswa melalui kegiatan observasi, pengumpulan data waktu nyata, dan analisis data. Literasi sains berkembang melalui pemahaman konsep secara kontekstual, sementara keterampilan abad ke-21, khususnya berpikir kritis, kreativitas, dan kolaborasi, diperkuat melalui pembelajaran berbasis masalah dan data. Namun demikian, efektivitas implementasi media pembelajaran berbasis IoT dipengaruhi oleh kesiapan infrastruktur dan kompetensi teknologi guru. Kajian ini menegaskan bahwa media pembelajaran berbasis IoT berpotensi menjadi inovasi strategis dan berkelanjutan dalam mendukung pembelajaran sains kontekstual di sekolah dasar.

Kata kunci: Keterampilan Abad 21, Literasi Sains, Media Pembelajaran IoT, STEM

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INTRODUCTION

The National Food Agency (Bapanas) reported that the Makan Bergizi Gratis (MBG) program has the potential to generate 1.1 to 1.4 million tons of food waste per year. The Head of the National Nutrition Agency stated that the government is already considering solutions for the waste generated by food leftovers from the MBG program. The food waste will be processed into compost, with a management mechanism that has been integrated into the program's ecosystem.

However, facts on the ground show that not all schools have adequate waste management mechanisms. The large amount of waste produced by schools in developing countries has not been managed through an effective and responsive system (Ramamoorthy et al., 2019). Based on the researchers' observations in elementary schools, it was found that limitations in the organic waste management system meant that food scraps from the MBG program in several schools were still being thrown into the trash. As a result, organic waste from MBG tends to accumulate because schools do not yet have a structured processing system.

This condition shows that organic waste management in schools is generally still traditional, namely only collected and disposed of without further processing. In addition to limited facilities and infrastructure, the lack of training for teachers and a teacher-centered approach to learning also limit opportunities for students to be actively involved in learning activities (Olaya et al., 2015). As a result, opportunities to develop students' skills through contextual learning have not been fully utilized. In fact, waste management is an important issue directly related to health and environmental conditions.

On the other hand, although schools have shown good participation in simple environmental activities such as tree planting and litter collection, involvement in sustainable practices such as composting is still low. This condition is influenced by science learning in the Merdeka Curriculum, which tends to be theory-oriented, as well as limited laboratory facilities (Syafitri et al., 2025). As a result, more in-depth waste management practices have not received attention and have not been optimally integrated into the daily learning process.

Given these conditions, teachers can raise the issue of organic waste as a learning context that is relevant to students' daily lives. This contextual learning can be realized through activities that process organic waste into compost. Thus, schools do not just wait for policies from outside but can start their own composting programs as school-based solutions. Organic waste management has the potential to be a meaningful learning medium for students (Widiantoro, 2023). Through activities such as waste sorting, processing food waste into compost, and utilizing compost for school plants, students can learn contextually and practically. This process not only instills environmental awareness but also develops critical thinking skills, responsibility, and a caring and disciplined attitude.

However, producing high-quality compost is not easy because the process requires temperature and humidity control, resulting in a lot of compost that is not fully matured (Hardyanti, 2019). This condition shows that the composting process requires measurable and consistent monitoring. Manual monitoring is often ineffective because it relies on observation using the five senses. Therefore, technological innovations are needed to assist in more accurate monitoring. The use of the Internet of Things (IoT) allows temperature and humidity sensors to be connected to digital devices so that data can be monitored in real-time (Carolina & Magalhães, 2025). With IoT, the compost management process becomes more controlled and has the potential to improve the quality of the fertilizer produced.

The integration of IoT in composting education not only helps optimize the composting process, but also provides a more in-depth and adaptive educational experience (Tsipianitis et al., 2025). Through these activities, students are trained to observe, analyze, and draw conclusions based on the data obtained. This type of learning has the potential to improve science literacy because students not only understand concepts theoretically but are also able to apply them in everyday contexts.

The urgency of strengthening context-based and sustainable learning is even more relevant when linked to the results of the 2022 PISA assessment. The data shows that the science literacy scores of Indonesian students (383) are still far below the OECD average (476), placing Indonesia 69th out of 80 countries in the. These findings indicate that science learning has not fully promoted a deep understanding of environmental and sustainability issues. In fact, the SDGs emphasize that education must be the primary means of building understanding of environmental and global issues, through the framework *of Education for Sustainable Development* (Vioreza et al., 2023). However, in reality, the application of SDG principles in the elementary school curriculum in Indonesia is limited and often not integrated with innovative learning methods (Afandi, 2025).

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In addition to low science literacy, various studies also show that the 21st-century skills of elementary school students in Indonesia, particularly critical thinking, creativity, collaboration, and communication (4C) skills, still need to be improved. A study conducted by (Widodo & Safitri, 2025) confirms that learning in Indonesia still tends to be memorization-oriented and has not fully developed higher-order thinking skills. The results of a study by (Wayudi & Santoso, 2020) research also show that Indonesian students' critical and creative thinking skills are still in the low to moderate category because learning does not provide many opportunities for students to solve real problems independently. This condition shows the need for learning innovations that can integrate everyday contexts with problem-based and technology-based approaches so that the development of 4C skills can run optimally (Rakhmawati et al., 2025).

Despite the increasing adoption of IoT technologies in environmental management and STEM education, existing studies remain fragmented and predominantly focus on technical implementation or isolated learning outcomes (Hastuti et al., 2026). There is limited systematic evidence that explains how IoT-based learning media function as pedagogical tools that link real-time data, contextual problem-solving, and student-centered learning processes to the development of science literacy and 21st-century skills in elementary education (Rakhmawati et al., 2024). Consequently, the conceptual relationship between IoT integration, contextual learning environments, and measurable learning outcomes remains underexplored.

Based on this urgency, a study is needed that specifically analyzes the use of technology as a learning medium relevant to the needs of the 21st century. Therefore, this study aims to analyze the effect of using IoT-based learning media on elementary school students' science literacy and 21st century skills, as well as to examine its advantages and limitations in the learning process. The results of this study are expected to serve as a reference for educators in selecting learning media that are appropriate for the needs of students in this ever-evolving digital age.

METHODS

This study uses a literature review approach with the Systematic Literature Review (SLR) method. This method is carried out through the stages of identification, examination, evaluation, and interpretation of various relevant studies. Researchers review articles that are relevant to the focus of the research question. Researchers reviewed articles relevant to the research question. The entire review process was conducted systematically and structurally by following the predetermined stages (Rahmi et al., 2023). Next, the researchers conducted an in-depth review of the articles that had been reviewed. The *Systematic Literature Review* technique was carried out through five stages, namely: (1) formulating research questions, (2) identifying and searching for articles relevant to the research questions, (3) conducting the inclusion and exclusion process through the selection and evaluation of the articles that had been collected, (4) presenting and analyzing data, and (5) interpreting research findings to obtain conclusions (Yusril et al., 2021).

The first step taken by the researchers was to determine the subject to be studied. The researchers chose the theme "Implementation of IoT-based STEM Learning Media on Science Literacy and 21st Century Skills of Elementary School Students" as the topic to be used in the study. Data collection for the literature study was carried out by searching for Google Scholar articles through the Publish or Perish (PoP) application using the keyword "IoT-based STEM learning in elementary school." The researchers limited the number of articles to 200 from 2021 to 2026. Then, the researchers filtered them again by selecting the contents of each article one by one. After analysis, 18 articles were found to meet the specified criteria. Next, from these various articles, the researcher will select 9 articles to be reviewed, analyzed, and re-examined in detail and related to the research theme. The following is a chart of the stages carried out by the researcher in conducting SLR literature studies through PoP.

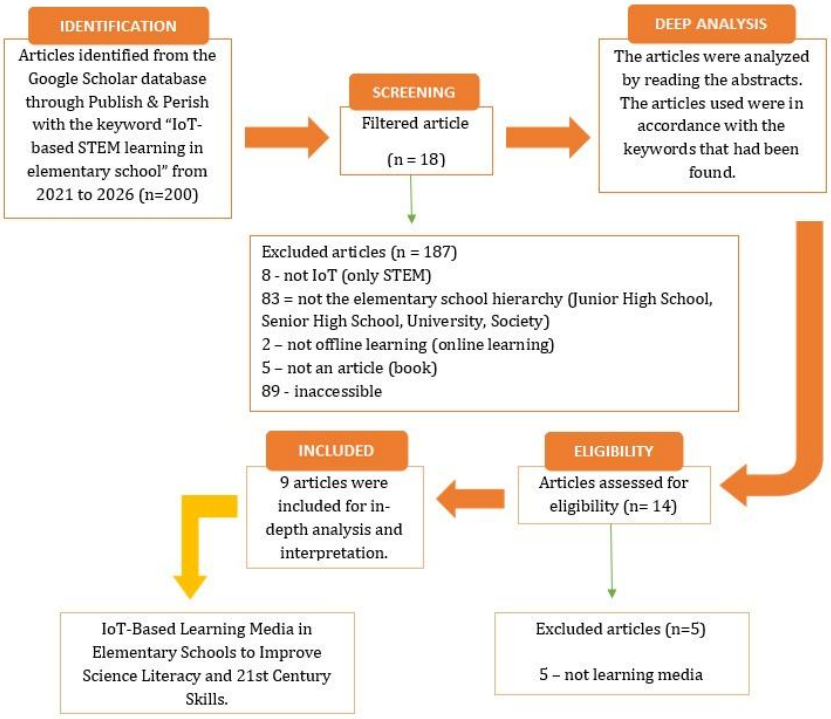

Figure 1. Flowchart of article exclusion and inclusion in the Systematic Literature Review process (n = number of articles)

RESULTS AND DISCUSSION

Results

The research data presented in this literature review is the result of analysis and summarization of various articles discussing the use of IoT learning media in learning activities in elementary schools.

Table 1. The Use of IoT-Based Learning Media in Elementary Schools to Improve Science Literacy and 21st Century Skills

No.	Author and Year	Journal	Research Results
1.	(Beng et.al, 2022)	Atlantis Press	The findings from this study indicate that STEM learning using IoT-based Plant Growth Sensor media can improve students' skills in recording, describing, and analyzing data. In addition, this model also supports the improvement of data literacy and simple statistical understanding in elementary school students
2.	(Khalid et.al, 2025)	ResearchGate	The findings from this study indicate that IoT-based STEM learning can develop students' technical skills while increasing environmental awareness, especially when the learning is linked to sustainability goals such as SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action).
3.	(Liston et.al., 2022)	Frontiers Media SA	The findings from this study indicate that the use of an IoT-based environmental monitoring system as an innovative data capture technology has a positive impact on the knowledge and skills of students and teachers in STEAM learning. Through data collection activities, such as measuring light, humidity, temperature, and sound in the school environment, IoT can help students understand concepts contextually while developing creative and imaginative mindsets.
4.	(Todorova et.al, 2025)	ABDIMAS UMTAS: Jurnal	The findings from this study indicate that the use of IoT sensors allows students to be directly involved in the problem-solving process, enabling

No.	Author and Year	Journal	Research Results
		Pengabdian Kepada Masyarakat	them to become active agents of change. The integration of IoT has been proven to improve critical thinking skills, creativity, and teamwork, as well as potentially strengthening sustainability competencies and encouraging behavioral change
5.	(Pratama et.al., 2025)	Jurnal Penelitian Pendidikan IPA	The findings from this study indicate that a projectbased STEM approach that integrates IoT technology is effective in improving science literacy. Through the design of sensor-based and IoT-based learning media, students not only produce innovative products but also improve their data interpretation skills, mastery of IoT technology, team collaboration, and integration of scientific concepts with real-world problems.
6.	(Sani et.al., 2024)	EDUMASPUL JURNAL PENDIDIKAN	The findings of this study conclude that the application of the IoT-based Problem-Based Learning (PBL) model has a significant effect on improving students' creative thinking skills, with an average effect size of 0.942, which is classified as high. The integration of IoT in PBL makes learning more contextual, relevant, and challenging because students are involved in reallife projects that require creative and innovative problem solving.
7.	(Lestari et.al., 2026)	Jurnal Atma Inovasia	The findings from this study indicate that IoT-based landslide miniature media effectively improves the science and technology literacy of elementary school students. Through soil moisture sensors, students can understand the relationship between environmental conditions and the potential for landslides in a more contextual way. The integration of IoT also helps explain geophysical concepts in a concrete way, supports SDGs 4, 11, and 13, and has the potential to become a model for disaster mitigation learning.
8.	(Qudwatullathifah et.al., 2026)	Jurnal Algoritma: Jurnal Ilmiah Bidang Ilmu Informatika	The findings from this study indicate that the IoT Playground system with the KERETA (Integrated Automatic Educational Home Energy Control) concept functions optimally in supporting interactive and contextual basic learning processes. User responses indicate a high level of practicality, with teachers giving a positive rating of 89.5% and students 86.7%, indicating that this tool is easy to use, safe, and visually appealing to elementary school children
9.	(Riansyah et.al., 2025)	ABDIMAS UNIVERSAL: Jurnal Pengabdian kepada Masyarakat	The results of this study indicate that the implementation of IoT-based hydroponic learning in elementary schools can provide students with practical and meaningful learning experiences. Students not only understand the basic concepts of hydroponics and IoT technology but also realize the importance of environmental sustainability. In addition to strengthening conceptual understanding, this approach has also been proven to improve students' critical, creative, and collaborative thinking skills.

Based on the research table above, the use of IoT-based learning media consistently shows a positive effect on elementary school students' science literacy and 21st-century skills. The results of these studies show that IoT is not only used as a technological tool, but also as a learning tool that helps students develop various important competencies. The use of IoT-based learning media can be used to support students in mastering 4C skills, namely creativity, critical thinking, and collaboration (Riansyah et al., 2025). In general, these findings can be grouped into three main aspects, namely increased literacy, strengthened 21st-century skills, and more contextual learning. Therefore, the following section will discuss these three aspects in more detail. From the table, identifiable patterns emerge that are illustrated in the Sankey diagram as follows.

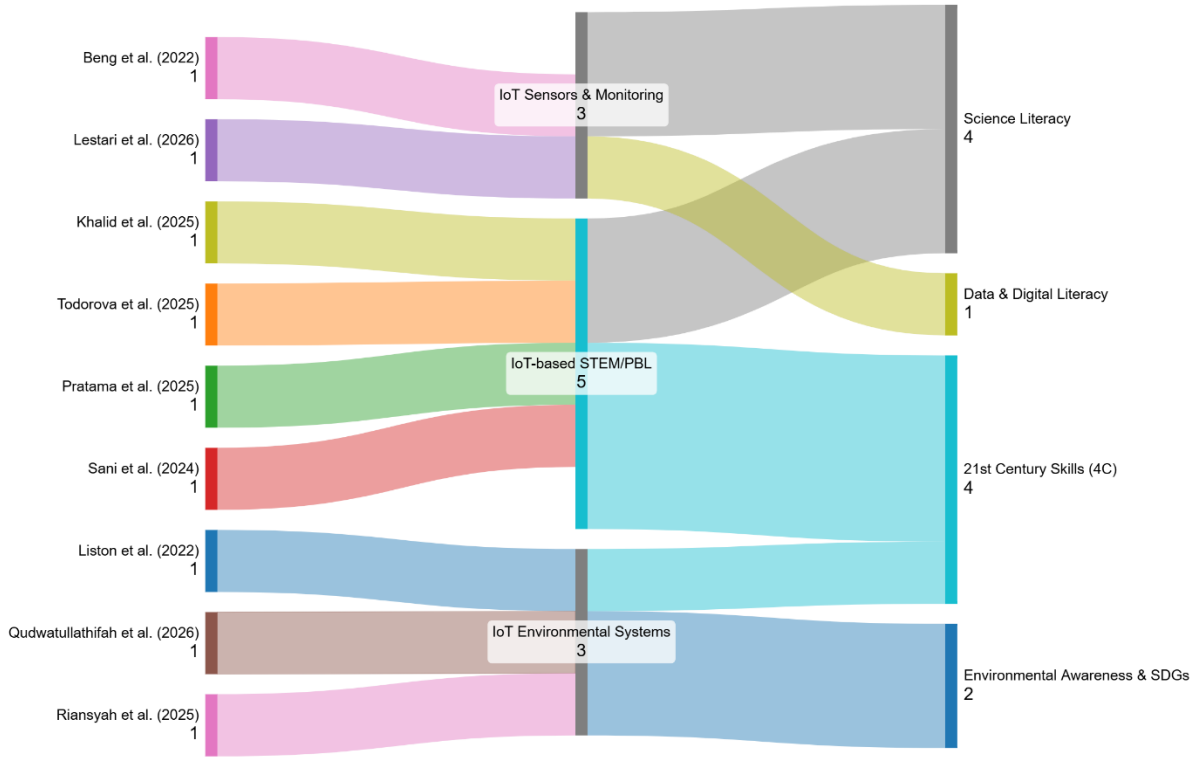

Figure 2. Patterns of IoT-Based Learning Media Integration

Based on the Sankey diagram, the findings reveal clear and consistent thematic patterns in the implementation of IoT-based learning media in elementary education. The reviewed studies can be conceptually grouped into three main IoT implementation focuses: IoT Sensors and Monitoring, IoT-based STEM/Problem-Based Learning (PBL), and IoT Environmental Systems, each demonstrating distinct relationships with specific learning outcomes. IoT Sensors and Monitoring are predominantly associated with improvements in science literacy, as sensor-based activities enable students to engage in direct observation, measurement, and data analysis, thereby fostering contextual and evidence-based understanding of scientific concepts, with a more limited but notable contribution to data and digital literacy. In contrast, IoT-based STEM/PBL emerges as the most dominant implementation pattern and shows the strongest linkage to the development of 21st-century skills, particularly critical thinking, creativity, and collaboration, through project-based and real-world problem-solving activities, while also contributing to science literacy as a supporting outcome.

Meanwhile, IoT Environmental Systems are most closely connected to the enhancement of environmental awareness and understanding of Sustainable Development Goals (SDGs), as learning activities centered on environmental monitoring and sustainability-oriented projects promote students' ecological responsibility and contextual learning, with complementary effects on 21st-century skills. Overall, the diagram demonstrates that the pedagogical impact of IoT-based learning media is not uniform but is shaped by instructional design and learning context, highlighting that sensor-based IoT primarily supports science literacy, IoT-integrated STEM/PBL strengthens 21st-century skills, and environmental IoT systems foster sustainability awareness, thereby underscoring the importance of contextual and problem-based integration of IoT to maximize learning outcomes in elementary education.

Discussion

The Role of IoT in Improving Student Literacy

The use of IoT-based learning media plays a role in improving the literacy of elementary school students, especially science literacy and digital literacy. Through IoT-based sensor devices and monitoring systems, students are directly involved in the process of collecting, recording, and analyzing data so that they learn to understand information in a structured manner and based on observation results. In STEM learning, the use of plant growth sensors helps students improve their data recording and analysis skills and understand simple statistics (Beng, Tji et al., 2022). A sensor-based test tool design project-based

approach has also been proven to strengthen students' science literacy through data interpretation activities (Pratama et al., 2025).

In addition, IoT helps bridge abstract concepts to make them more concrete through contextual learning experiences. The use of sensor-based landslide miniatures, for example, makes it easier for students to understand the relationship between environmental conditions and potential disasters directly (Lestari, Anastasia, Kadek et al., 2026) . By utilizing real data from the surrounding environment, learning becomes more meaningful and easier to understand. The integration of IoT not only introduces technology in the classroom, but also builds students' abilities to understand, process, and interpret data as part of a comprehensive literacy process.

Beyond procedural data skills, IoT also plays a critical role in making abstract scientific concepts more concrete through contextualized learning experiences. Compared to more general sensor-monitoring activities, these context-specific implementations appear to foster deeper conceptual literacy, indicating that the learning context significantly mediates IoT's pedagogical effectiveness. From a practical perspective, these findings imply that IoT-based learning media are most effective for literacy development when used not merely as technological tools, but as integral components of inquiry-driven and context-rich instructional designs. However, the reviewed studies also share limitations that warrant critical consideration, including small sample sizes, short intervention durations, and limited discussion of long-term literacy outcomes. In addition, most studies focus on immediate learning gains, leaving the sustainability of literacy development underexplored. These limitations highlight the need for future research to employ longitudinal designs and to examine how different instructional models moderate the relationship between IoT integration and student literacy outcomes.

IoT and Strengthening 21st Century Skills

The integration of IoT in learning contributes to strengthening the 21st century skills of elementary school students, such as critical thinking, creativity, and collaboration. In line with this, the integration of IoT technology provides integrated learning based on science, mathematics, technology, and art that not only emphasizes mastery of the material but also shapes students' 21st century skills and environmental awareness (Liston et al., 2022) and (Khalid et al., 2025).

Through IoT-based learning media, students are presented with real-life situations that require them to identify problems, use tools, analyze data, and design and evaluate solutions. The IoT-based Problem-Based Learning (PBL) model has even shown a significant effect on improving students' creative thinking skills in the high category (Sani et al., 2024). This shows that active involvement in technology-based projects can encourage students to think more innovatively and reflectively. In addition, the use of IoT sensors also trains students to understand the relationships between interdependent factors and to work together to solve problems (Todorova et al., 2025).

In IoT-based hydroponics learning, students not only understand concepts but also improve their critical, creative, and collaborative thinking skills through continuous system design and monitoring activities (Riansyah et al., 2025). Thus, IoT functions not only as a technological tool but also as a strategic means of supporting the strengthening of 21st century competencies in learning.

That highlight collaboration and reflective thinking as emergent outcomes of sustained engagement with data-driven systems. In contrast to short-term interventions, these iterative learning models appear to better support the development of collaboration and systems thinking, as students must negotiate roles, interpret interconnected variables, and refine solutions collectively (Rakhmawati et al., 2023). From a practical standpoint, these findings imply that educators should prioritize pedagogical designs that integrate IoT within problem-based, project-based, and collaborative learning frameworks to maximize 21st-century skill development. IoT should function as a cognitive tool that supports inquiry, reflection, and teamwork, rather than as an end. Nevertheless, the reviewed studies also present notable limitations, including reliance on short intervention periods, limited assessment of communication skills, and insufficient exploration of long-term skill transfer. These constraints suggest the need for future research to adopt longitudinal designs and more comprehensive assessment frameworks to better capture the sustained impact of IoT-based learning on 21st-century competencies.

Contextual and Problem-Based Learning

The reviewed studies indicate that IoT integration meaningfully supports contextual and problem-based learning by situating scientific concepts within real-world environments and data-driven activities. However, comparative analysis across studies suggests that the depth of contextual learning achieved

varies according to how IoT is pedagogically embedded. The use of IoT in learning encourages the creation of a more contextual and problem-based learning process. Through IoT-based sensor devices and monitoring systems, students not only learn concepts theoretically, but also observe and analyze data from the real environment. This activity makes learning more relevant to everyday life and helps students understand the relationship between the concepts they learn and the situations around them. In projectbased learning, the integration of IoT allows students to design and develop products that can be used in real life, making learning more meaningful (Pratama et al., 2025)

In addition, the IoT-based approach in the PBL model presents challenges that encourage students to actively engage in systematic problem solving. Through projects related to environmental and sustainability issues, students are trained to identify problems, collect data, and formulate appropriate solutions (Todorova et al., 2025). IoT-based environmental monitoring system learning media engages students in real-life situations, thereby improving their understanding of concepts and raising their awareness of environmental issues (Riansyah et al., 2025). Thus, IoT serves as a bridge between theory and practice, making learning more contextual, challenging, and problem-solving oriented.

From an instructional perspective, these results imply that educators should integrate IoT within learning designs that emphasize authentic problems, sustained investigation, and reflective analysis to maximize its contextual value. IoT should be positioned as a bridge between theory and practice, enabling students to test concepts against real-world data and conditions. Nevertheless, the reviewed studies also reveal important limitations, including short implementation periods, limited discussion of instructional scaffolding, and insufficient evaluation of long-term problem-solving skill development. These gaps indicate a need for future research to explore how sustained and well-scaffolded IoT-based problem learning influences conceptual understanding and transferable problem-solving skills over time.

Although various studies show that IoT-based learning media have many advantages, their implementation in education is not without challenges. The application of IoT requires infrastructure readiness, including a stable internet network, availability of sensor devices, and installation costs (Imran et al., 2025) and (Shafique et al., 2021). In addition, teacher readiness and technological literacy are key factors in the successful use of IoT in the classroom, so adequate training is essential. Data security and privacy aspects also need to be considered because IoT systems involve digital data collection and management (Prasetya, Luhur et al., 2025). Therefore, although IoT offers great potential for improving the quality of learning, its implementation requires careful planning, technical support, and appropriate policies to ensure optimal and sustainable operation.

CONCLUSION

The advancement of the industrial era has significantly transformed educational practices, particularly through the integration of technologies such as the Internet of Things (IoT). This review demonstrates that IoT-based learning media effectively enhance elementary school students' science literacy and strengthen essential 21st-century skills, including critical, creative, and collaborative thinking, by enabling data-driven and contextual learning experiences that bridge theory and practice. From a practical perspective, the findings suggest that teachers should integrate IoT within problem-based and project-based learning designs to maximize its pedagogical value, rather than using IoT solely as a technical tool. At the policy level, the results highlight the need for targeted investment in school infrastructure, reliable internet access, and the provision of IoT learning devices, as well as systematic professional development programs to improve teachers' technological and pedagogical competence. Furthermore, curriculum developers and education authorities are encouraged to explicitly embed IoT-supported contextual learning within science and STEM curricula to support sustainability education and the development of 21st-century competencies. Overall, with appropriate instructional design and policy support, IoT-based learning media can serve as a strategic and sustainable innovation in elementary education.

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