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# Mapping the State of the Art of ESP32-Based Robotics for STEM Physics Education

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**Abstract**
The rapid development of Industry 4.0 has driven increased demand for physics education that fosters science process skills and problem-solving abilities through technology-integrated learning. This study surveys the current state of ESP32-based educational robotics integrated with STEM approaches in physics education and identifies research gaps. A systematic review was conducted on publications from 2020 to 2025 in reputable databases, including Scopus, Springer, IEEE Xplore, MDPI, and Taylor & Francis. Bibliometric analysis using VOSviewer examined research trends, thematic patterns, and emerging topics. Results reveal a surge in studies on STEM, educational robotics, and IoT, though most focus on general learning outcomes, motivation, or conceptual frameworks. Few studies explicitly design ESP32-based robotic tools as experimental resources to support quantitative physics inquiry and science process skills. This review emphasizes the need for structured ESP32-based robotics combined with STEM and project-based learning to improve data-driven physics experiments. The results offer a conceptual foundation for future research in STEM-based physics learning media.

**Keywords:**
STEM-integrated physics education, educational robotics, ESP32-based learning media, science process skills, problem-solving skills

## INTRODUCTION

The rapid development of science and technology in the 21st century has fundamentally transformed the demands placed on education systems, particularly in the fields of science and technology. The Fourth Industrial Revolution, characterized by the integration of cyber–physical systems, the Internet of Things (IoT), and intelligent automation, requires graduates not only to master conceptual knowledge but also to possess higher-order thinking skills, problem-solving abilities, and the capacity to use technology adaptively (Onu et al., 2024; Mintii, 2023). In this context, science education, especially physics, plays a strategic role as a foundation for developing scientific literacy and STEM (Science, Technology, Engineering, and Mathematics) competencies needed to address global challenges (Le et al., 2023).

Physics has unique characteristics as a discipline because it connects scientific theory with technological applications. However, research evidence indicates that physics learning continues to face serious challenges, particularly related to students' low science process skills and problem-solving abilities (Musengimana et al., 2025; Lotriet & Gouws, 2025). Physics is often perceived as abstract, mathematically demanding, and disconnected from real-life contexts, making it difficult for students to develop deep conceptual understanding and apply knowledge in new situations (Uslu & Yavuz, 2023). These conditions contribute to low interest in STEM fields and limit students' readiness to meet the demands of a technology-driven workforce (Astuti et al., 2021; Mintii, 2023).

In response to these challenges, STEM-based learning approaches have been widely recommended as a strategy to transform science and physics education. STEM emphasizes the integration of scientific concepts with technology and engineering through authentic problem-solving activities relevant to real-world contexts (Le et al., 2023; Darmawansah et al., 2023). Systematic reviews have shown that STEM approaches significantly contribute to the development of critical thinking, problem-solving skills, and science process skills by actively engaging students in investigation, design, and testing processes based on scientific principles (Astuti et al., 2021; Pinar et al., 2025). Thus, STEM education is oriented not only toward content mastery but also toward the development of applicable scientific competencies (Tassilova & Shashayeva, 2025).

Along with advances in educational technology, STEM integration has been strengthened through the use of technology-based learning media, such as educational robotics and IoT systems. Educational robotics is considered an effective medium for bridging the gap between abstract physics concepts and concrete learning experiences (Sherwani & Asad, 2023; Kalaitzidou & Pachidis, 2023). Through direct interaction with robots, students can observe physical phenomena, conduct measurements, and analyze data in real time (Wang et al., 2024). Meta-analyses and systematic reviews consistently report that the use of educational robots in STEM learning positively affects learning performance, attitudes toward science, and students' problem-solving and scientific thinking abilities (Ouyang & Xu, 2024; Sapounidis & Tselegkaridis, 2024; Wang et al., 2023).

In the context of learning technology, the use of low-cost and open-source microcontrollers, such as the ESP32, has received increasing attention in STEM education. The ESP32 offers adequate computational capability, integrated wireless connectivity, and compatibility with various sensors, enabling the development of experiment-based and data-driven learning media (Abichandani et al., 2022; Ghashim & Arshad, 2023). Nevertheless, the use of ESP32 in education remains largely focused on programming instruction or general IoT applications (Pacala et al., 2025; Karalekas et al., 2023). Its potential as a systematically designed physics learning medium to foster science process skills and problem-solving abilities has not been extensively explored (Tassilova & Shashayeva, 2025).

From a pedagogical perspective, Project-Based Learning (PjBL) is frequently combined with STEM approaches and educational robotics to create meaningful learning experiences. PjBL positions students as designers and problem solvers through projects that require the application of interdisciplinary knowledge (Chistyakov et al., 2023; Manasikana & Saputro, 2025). The integration of STEM, PjBL, and robotics enables students to engage in complete scientific processes, from problem identification and physics-based solution design to evaluation through experimental data (Roslina & Samsudin, 2022). However, the literature indicates that many implementations still focus on the effectiveness of learning models, without explicitly linking robotic media design to indicators of science process skills and physics problem-solving (Amalina & Vidákovich, 2022; Wang et al., 2024).

Based on a review of recent studies, a gap can be identified between the potential of ESP32-based robotic technology and current physics teaching practices. Although educational robotics and STEM approaches have demonstrated general effectiveness, limited research has focused on developing robotics-based physics learning media specifically designed to support quantitative experimentation, data analysis, and systematic development of science process skills (Lotriet & Gouws, 2025; Uslu & Yavuz, 2023). This gap highlights the need for a more integrated approach that aligns technology, pedagogy, and physics content (Darmawansah et al., 2023; Deehan et al., 2025).

Therefore, this study aims to present a preliminary investigation based on a systematic literature review to map research developments, potential, and gaps related to the development of STEM-integrated ESP32-based robotic media for physics learning. This article is expected to provide a strong conceptual foundation for the development of contextual, data-driven physics learning media that align with the demands of 21st-century education, as well as serve as a basis for subsequent development-oriented research (Tassilova & Shashayeva, 2025; Abichandani et al., 2022).

In addition, the urgency of this research is reinforced by the increasing demand for learning models that are not only technologically enriched but also empirically grounded in measurable learning outcomes. Many existing innovations in STEM and robotics-based learning remain fragmented, often emphasizing technological novelty without sufficient alignment to core physics competencies such as science process skills and analytical problem-solving. This condition creates a gap between instructional innovation and actual learning effectiveness. Therefore, it is essential to systematically examine how ESP32-based robotic media can be designed to explicitly support measurable cognitive and scientific skill development within physics learning contexts.

Furthermore, this study holds strategic importance in contributing to the advancement of research-based instructional design in physics education, particularly in developing countries where access to high-cost laboratory equipment is limited. By leveraging low-cost, open-source technologies such as ESP32, this research offers a scalable and accessible alternative for implementing data-driven and experiment-based learning. In this regard, the study not only addresses theoretical gaps but also provides practical implications for educators and curriculum developers in designing inclusive and technology-integrated physics learning environments. Thus, this research is expected to bridge the gap between technological potential and pedagogical implementation while promoting equitable access to high-quality STEM education.

## METHOD

This study employed a systematic literature review approach to map research trends, empirical findings, and research gaps related to the development of STEM-integrated educational robotics for physics learning, with a particular focus on improving science process skills and problem-solving abilities. The review was limited to scholarly publications from the last five years (2020–2025) to ensure the relevance and currency of the identified state of the art.

Data sources were obtained from reputable and high-impact academic databases, including Scopus-indexed journals and international conference proceedings published by Springer, Elsevier, IEEE Xplore, MDPI, Taylor & Francis, and the Eurasia Journal of Mathematics, Science and Technology Education. These sources were deliberately selected due to their rigorous peer-review processes, high citation impact, and strong relevance to interdisciplinary research in STEM education, educational technology, and applied physics. In addition, these databases are widely recognized for indexing cutting-edge studies in robotics, Internet of Things (IoT), and science education, ensuring the credibility, validity, and contemporaneity of the literature included in this review. Therefore, the selection of these publication sources was intended to ensure that the analysis is grounded in authoritative and high-quality scientific evidence.

The literature search employed a set of systematically integrated keywords, including STEM education, educational robotics, ESP32, Internet of Things in education, physics education, science process skills, and problem-solving skills. These keywords were selected based on their conceptual relevance to the intersection of technology, pedagogy, and physics content, as well as their frequent use in prior high-impact publications within the field. The combination of these terms was designed to capture studies that specifically address the integration of low-cost microcontroller-based robotics within STEM-oriented physics learning environments. Furthermore, the inclusion of terms such as science process skills and problem-solving skills reflects the study's focus on measurable learning outcomes, ensuring that the retrieved literature aligns with the research objectives. Thus, the keyword selection strategy was structured to maximize both the breadth and specificity of relevant literature coverage.

Articles were selected based on the following inclusion criteria: (1) studies addressing the implementation of STEM, robotics, or IoT in science or physics education; (2) studies employing empirical research designs, systematic reviews, or meta-analyses; and (3) studies reporting impacts on higher-order thinking skills. The selected data were analyzed qualitatively through content analysis and thematic synthesis to identify patterns of findings, research trends, and existing research gaps. The results of this synthesis were used as a conceptual basis for determining directions for the development of ESP32-based, STEM-integrated physics learning media.

The analysis was conducted in two stages. First, bibliometric analysis was performed using VOSviewer to generate visualizations of publication trends, keyword networks (network visualization), temporal development of research themes (overlay visualization), and the density of research focus areas (density visualization). Second, qualitative analysis through content analysis and thematic synthesis was used to interpret the bibliometric findings, identify dominant research patterns, and formulate research gaps. This integrated analysis provided the conceptual foundation for mapping the potential and future directions of STEM-integrated ESP32-based robotics for physics education.

## RESULTS AND DISCUSSION

### Research Trends in STEM-Integrated Educational Robotics and IoT for Physics Education

Figure 1 illustrates a pronounced and accelerating growth in research publications addressing STEM-integrated educational robotics and Internet of Things (IoT) applications in physics education between 2016 and 2025. The relatively modest and stable number of studies prior to 2019 suggests that early research primarily explored the conceptual potential of robotics and IoT within STEM education. In contrast, the sharp increase observed from 2020 onward marks a clear shift toward empirical validation and broader adoption of technology-enhanced learning environments. This escalation reflects a growing recognition that conventional physics instruction is insufficient for developing higher-order competencies, particularly science process skills and problem-solving abilities, which are increasingly demanded in contemporary STEM education.

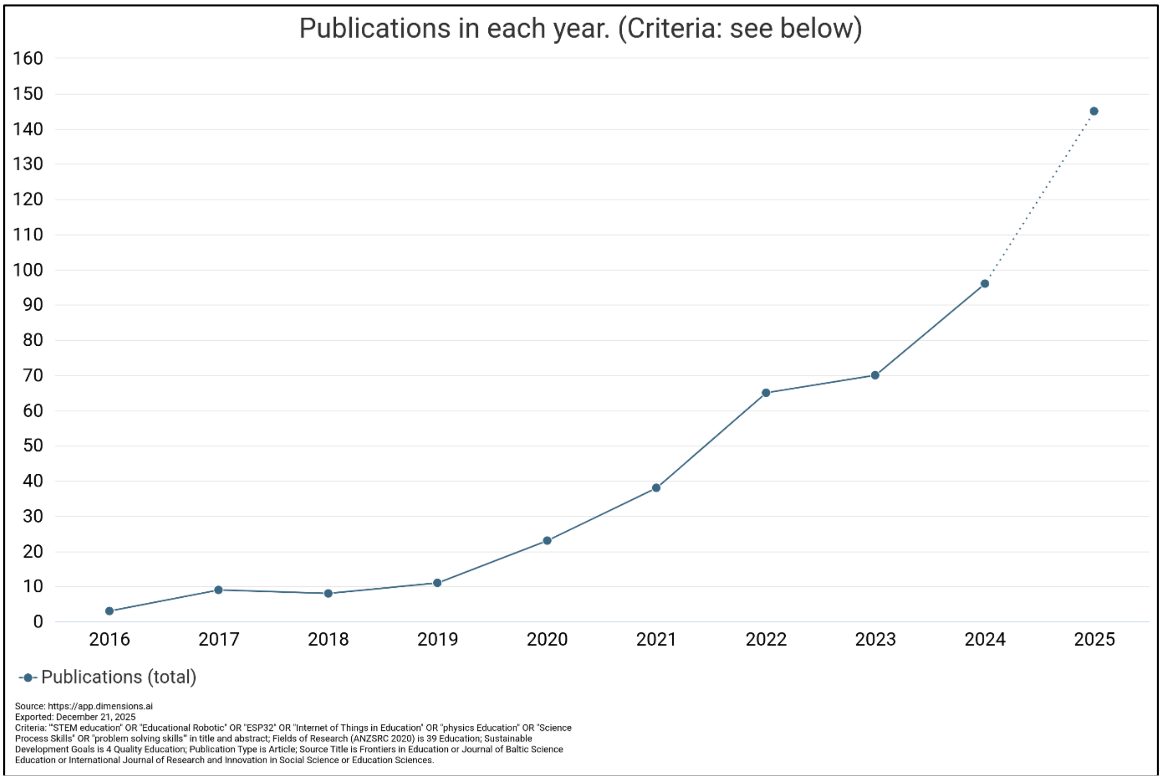


**Figure 1.** Research Trends in STEM-Integrated Educational Robotics and IoT for Physics Education (2016–2025)

Despite the rapid expansion of this research domain, the observed publication trend also reveals a critical imbalance between research quantity and conceptual depth. A substantial proportion of existing studies concentrates on general learning outcomes, engagement, or motivational aspects, often treating robotics and IoT as supplementary instructional tools rather than as core experimental media for physics learning. Consequently, physics is frequently positioned as a contextual backdrop instead of being addressed as an experimental, data-driven discipline that requires systematic inquiry and analysis. This trend highlights a significant research gap: the lack of well-designed physics learning media that leverage ESP32-based robotics to integrate sensor-based experimentation, real-time data acquisition, and structured problem-solving within a STEM framework (Al-Qoyyim & Doyan, 2023; Dwiyanti et al., 2023; Mulyono et al., 2024). Addressing this gap is essential to advance the field beyond demonstrating effectiveness toward establishing robust, discipline-specific pedagogical innovations.

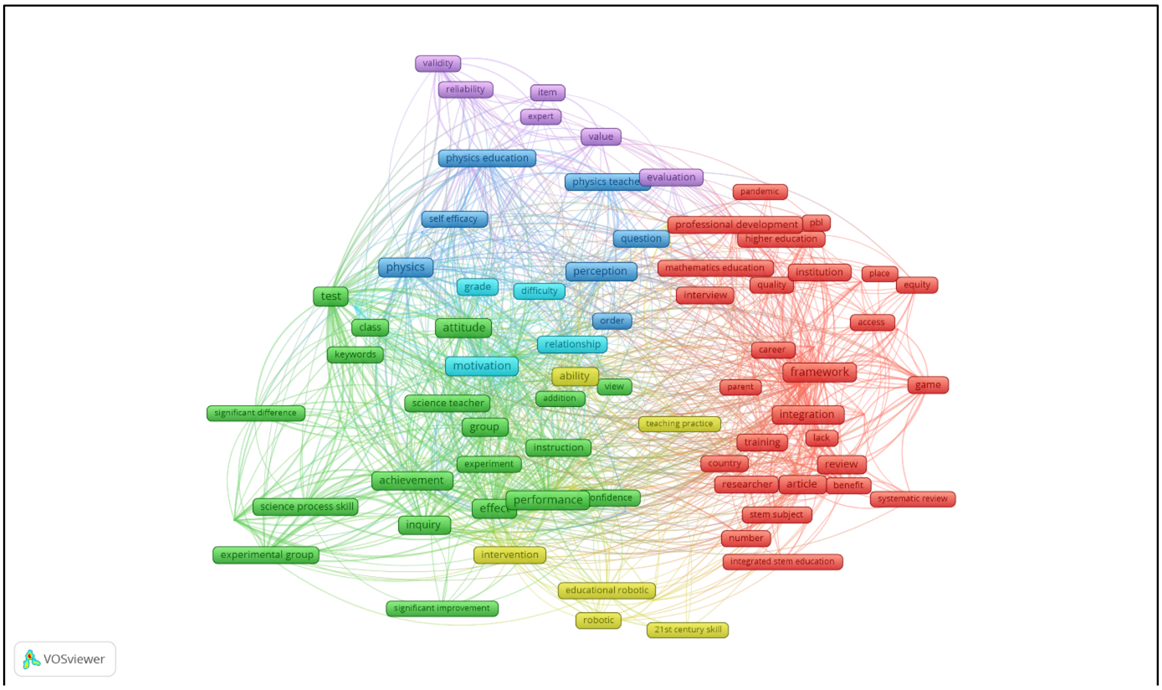


**Figure 2.** Network Visualization

The bibliometric network visualization generated using VOSviewer indicates that research in physics education and STEM is organized into several interconnected clusters with distinct thematic emphases. The green and blue clusters dominate the network and are characterized by keywords such as physics, science process skill, experiment, performance, achievement, motivation, and attitude. This pattern suggests that most studies focus on measuring the impact of instructional interventions on learning outcomes and affective variables. The strong links among experiment, instruction, intervention, and science teacher further indicate that physics continues to be framed as an experiment-based learning domain; however, these experiments are generally interpreted within conventional pedagogical approaches. In contrast, the purple cluster, which includes keywords such as validity, reliability, evaluation, and item, reflects a substantial research focus on instrument development and validation rather than on innovation in learning media or educational technology (Al-Qoyyim, Nabila, et al., 2024).

Although keywords such as educational robotic, robotic, 21st century skill, and integrated STEM education appear in separate clusters (yellow and red), their positions are relatively peripheral and weakly connected to the science process skill and experimental inquiry clusters (Evripidou et al., 2020; Ioannou & Makridou, 2018; Lotriet & Gouws, 2025; Pozzi et al., 2021). This pattern indicates that robotics and STEM research is more frequently positioned at the level of conceptual frameworks, policy discussions, or general reviews, rather than as physics experimental media that explicitly foster data-driven science process skills and problem-solving. This separation highlights a significant research gap, namely the absence of a strong conceptual and empirical bridge between educational robotics as a technological artifact and physics as an experimental science grounded in measurement and data analysis. Therefore, the development of STEM-integrated ESP32-based robotic learning media for physics is both relevant and strategic, as it can integrate these clusters and shift the research focus from general effectiveness toward authentic, data-driven media design that supports science process skills and 21st-century problem-solving abilities (Abdjul et al., 2022; Herlinawati et al., 2024; Kartini et al., 2022).

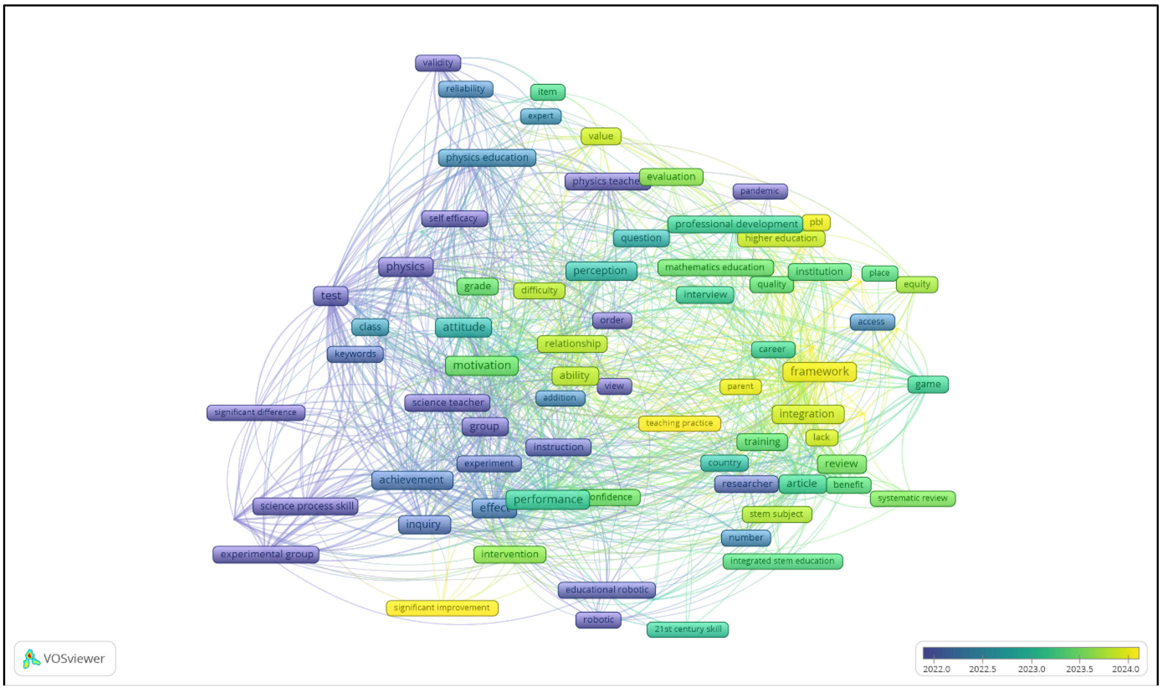


**Figure 3.** Overlay Visualization

The overlay visualization shows a clear shift in research focus from traditional pedagogical and evaluative themes toward technology integration and 21st-century skills in physics and STEM education. Keywords displayed in darker colors (blue–purple), such as test, experimental group, science process skill, significant difference, and achievement, represent an early research phase dominated by quasi-experimental designs and the measurement of learning effectiveness based on achievement outcomes (Al-Qoyyim et al., 2022; Anwar et al., 2024; Jelita & Mazlan, 2023; Nisa et al., 2023). This focus positions physics primarily as an evaluative domain, with an emphasis on demonstrating differences in learning outcomes between groups. Over time, a transition emerges toward keywords shown in green, reflecting increased attention to affective and higher-level cognitive aspects, such as motivation, attitude, performance, confidence, and ability, indicating a growing concern for learning processes and the quality of students' learning experiences.

Keywords shown in the brightest color (yellow) represent the most recent research themes, including educational robotic, integrated STEM education, framework, integration, 21st century skill, and teaching practice. This pattern indicates that recent studies increasingly emphasize STEM and robotics integration as strategic learning frameworks to address 21st-century competency demands. However, the overlay visualization also reveals that keywords related to educational robotics and integrated STEM education remain weakly connected to science process skill and experimental inquiry, which appeared earlier in the literature (Najjar & Daher, 2023; Wen et al., 2023; Yuliana et al., 2021). This pattern suggests a temporal and conceptual gap in which robotics and STEM are still discussed more frequently at the level of frameworks, integration, and general practices rather than as data-driven physics experimental media grounded in measurement and empirical analysis. Therefore, the development of STEM-integrated ESP32-based robotic physics learning media is relevant to bridge earlier research focused on science process skills with emerging trends in robotics, IoT, and 21st-century skills in a more substantive and operational manner.

The density visualization highlights areas of highest concentration (bright yellow) centered on keywords such as framework, integration, motivation, attitude, performance, effect, and achievement. This pattern indicates that recent research in physics education and STEM has been heavily focused on the development of conceptual frameworks, the integration of learning approaches, and the measurement of their effects on learning outcomes and students' affective variables. The high density of these terms suggests that learning effectiveness and STEM integration have become mainstream themes in the literature. Meanwhile, keywords such as physics education, test, and evaluation appear with moderate density, reflecting a strong research tradition in learning evaluation and assessment of physics learning outcomes (Al-Qoyyim, Wahyudi, et al., 2024; Al-Qoyyim & Nabila, 2025; Nabila & Al-Qoyyim, 2025).

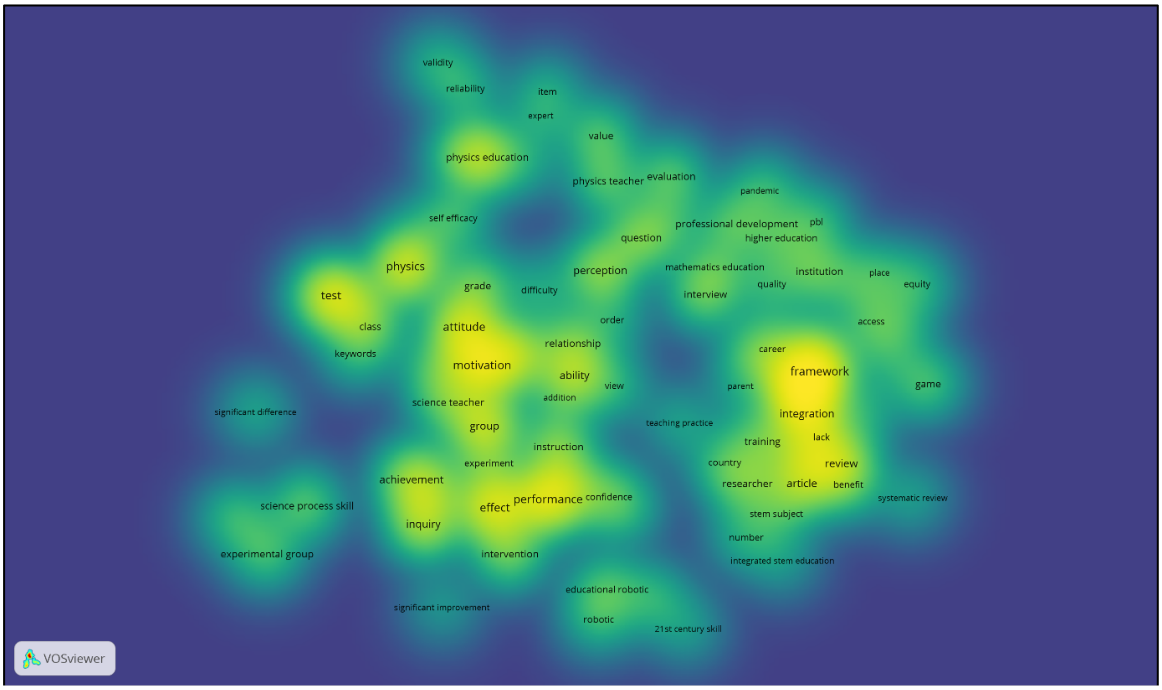


**Figure 4.** Density Visualization

In contrast, areas with lower density (green–blue) include keywords that are highly relevant to the focus of this study, such as science process skill, educational robotic, robotic, experimental group, and 21st century skill. The lower density of these keywords indicates that although robotics, STEM, and science process skills are frequently mentioned, they have not yet become central, integrated research themes. In particular, educational robotic and science process skill appear distant from the core density areas, suggesting that robotics is still rarely used as a physics experimental medium explicitly designed to develop measurement-based scientific processes and data analysis skills. These findings highlight a strong research opportunity to develop STEM-integrated ESP32-based robotic physics learning media that move beyond conceptual frameworks toward authentic, data-driven enhancement of science process skills and problem-solving abilities.

**Transformation of Physics Learning in the Context of STEM and Industry 4.0**

The rapid advancement of science and technology in the era of Industry 4.0 has brought significant implications for the direction and goals of science education, particularly physics learning. Physics education is no longer understood solely as a process of transferring concepts and natural laws, but as a strategic means of equipping students with 21st-century skills such as problem-solving, critical thinking, creativity, collaboration, and technological literacy. Recent systematic studies indicate that the demands of modern life and the workforce position problem-solving and scientific inquiry as core competencies that must be intentionally developed through physics education (Onu et al., 2024; Mintii, 2023).

Nevertheless, physics remains one of the subjects commonly perceived as difficult by students across educational levels. This difficulty is generally attributed to the abstract and mathematical nature of physics, as well as the limited connection between theoretical concepts and observable real-world phenomena. Musengimana et al. (2025) emphasize that weak physics problem-solving ability often stems from low science process skills, including observing, problem formulation, experimental design, data interpretation, and evidence-based conclusion drawing. These conditions may reduce students' interest in STEM fields and hinder the holistic achievement of science education goals.

In this context, STEM (Science, Technology, Engineering, and Mathematics)-based learning approaches have emerged as a strategic response to the need for transformation in physics education. STEM is viewed as an approach capable of integrating scientific concepts with technology and engineering through authentic problem-solving activities relevant to real-life contexts. Le et al. (2023) report that integrated STEM approaches, particularly those involving engineering challenges, consistently contribute to the development of higher-order thinking skills, including science process skills and problem-solving abilities. This approach positions students as active problem solvers rather than passive recipients of information.

Furthermore, recent literature highlights that effective STEM implementation requires support from concrete and interactive learning technologies. Tassilova et al. (2025), in their systematic review, report that STEM learning trends over the past five years show a significant shift toward the use of communication technologies, microcontroller-based devices, sensors, and robotics to create hands-on and inquiry-based learning experiences. Such technologies enable students not only to understand physics concepts conceptually but also to test them through controlled experiments that generate real data.

The link between STEM education and the demands of Industry 4.0 further reinforces the urgency of transforming physics learning. Onu et al. (2024) argue that STEM education plays a critical role in preparing learners to adapt to industrial ecosystems driven by automation, the Internet of Things (IoT), and artificial intelligence. In this context, mastery of science process skills and problem-solving abilities is inseparable from the ability to use technology as a tool for data analysis and evidence-based decision making. Physics instruction that remains focused on formula memorization and routine problem solving is therefore no longer sufficient to meet these challenges.

On the other hand, several systematic reviews reveal a gap between curriculum expectations and actual classroom practices in physics education. Although STEM has been widely recommended as an ideal approach, its implementation often remains at a conceptual or instructional model level, without adequate learning media and infrastructure to support genuine integration of science, technology, and engineering (Arafat et al., 2024; Amalina & Vidákovich, 2022). As a result, the development of science process skills and problem-solving abilities has not been optimal, particularly in physics learning contexts that require experimentation and quantitative measurement.

Therefore, the transformation of physics learning within the context of STEM and Industry 4.0 requires the development of learning media that are not only pedagogically innovative but also technologically relevant. Technology-based learning media, such as educational robotics and IoT systems, have the potential to bridge abstract physics concepts with real-world applications. This approach aligns with global research trends that emphasize contextual, project-based, and problem-oriented learning as the foundation of 21st-century physics education. This section provides the conceptual basis for understanding why the development of STEM-integrated robotics-based physics learning media is both urgent and scientifically relevant.

**Educational Robotics and ESP32 as STEM Learning Media in Physics**

The development of educational robotics over the past decade has shown a significant increase in both the number of publications and the diversity of implementation contexts. Recent systematic reviews and meta-analyses confirm that educational robots are effective learning media for supporting STEM education because they integrate physical activity, programming, and problem-solving within an authentic learning ecosystem. Ouyang and Xu (2024), through a multilevel meta-analysis, reported that the use of educational robotics produced moderate and significant effects on students' learning performance and attitudes in STEM learning compared to non-robotic approaches. These findings indicate that robots function not merely as instructional tools, but as cognitive artifacts that mediate the learning process.

In the context of science and physics education, educational robotics offers particular advantages in bridging abstract concepts with observable and manipulable real-world phenomena. Lotriet and Gouws (2025) emphasized that the use of robots in physics learning contributes positively to conceptual understanding, problem-solving abilities, and the development of scientific meta-competencies such as critical, creative, and systems thinking. Robots enable students to conduct controlled experiments, observe cause–effect relationships, and test physics-based predictions through directly generated empirical data.

Nevertheless, the literature also indicates that the effectiveness of educational robotics is strongly influenced by pedagogical design and the characteristics of the technology used. Wang et al. (2024), using the Technological Pedagogical Content Knowledge (TPACK) framework, revealed that many classroom implementations of physical robots remain demonstrative in nature and do not yet fully integrate science content in depth. This finding highlights the need for robotic learning media specifically designed for physics learning objectives, rather than adaptations from general technology or programming contexts.

With the expansion of the Internet of Things (IoT) paradigm, the use of low-cost and open-source microcontrollers has become increasingly prominent in educational robotics research. Abichandani et al. (2022) noted that ESP modules, including the ESP32, are among the most widely recommended hardware platforms in IoT curricula for STEM education due to their flexibility, scalability, and suitability for project-based learning. The ESP32 offers advantages such as integrated Wi-Fi and Bluetooth connectivity, adequate processing capability, and compatibility with various sensors, enabling the development of educational robots capable of conducting real-time physics measurements.

In studies on robotics in STEAM education, Kalaitzidou and Pachidis (2023) reported that the ESP32 is frequently used in modern educational robots, alongside platforms such as Arduino and Raspberry Pi. However, the use of ESP32 in educational contexts generally remains focused on technical aspects of programming and control, while its potential as a physics learning medium for experimental investigation and data analysis has not been fully utilized. This observation aligns with the findings of Karalekas et al. (2023), who reported that although ESP32 has been implemented in certain educational robots, its use is more strongly oriented toward technological and computational learning rather than the development of science process skills.

From a pedagogical perspective, integrating ESP32-based educational robotics into STEM learning enables the simultaneous application of design-based learning and inquiry-based learning approaches. Students do not merely interact with robots as users, but actively engage in designing, building, programming, and testing robotic systems to solve contextual problems. Uslu et al. (2023) emphasized that this approach contributes significantly to the development of higher-order thinking skills, including science process skills and problem-solving abilities, as students are required to formulate hypotheses, analyze data, and revise solutions based on experimental results.

Furthermore, integrating ESP32 with the IoT ecosystem provides opportunities to enrich physics learning through digital data collection and visualization. Ghashim and Arshad (2023) demonstrated that IoT-based learning can enhance learning experiences by providing real-time feedback and enabling continuous performance analysis. In physics education, these capabilities are highly relevant for training students to interpret data, identify patterns, and draw evidence-based conclusions.

Therefore, ESP32-based educational robotics has strong potential as STEM-integrated physics learning media. However, the synthesis of existing literature indicates an urgent need to develop robotic learning media designs that explicitly target the development of science process skills and physics problem-solving abilities. This section emphasizes the position of the ESP32 not merely as a technical component, but as a key element in the development of contextual, authentic, and STEM-aligned physics learning media that meet the demands of 21st-century education.

**Integration of STEM, Project-Based Learning, and Robotics in Developing Science Process Skills and Problem-Solving Abilities**

The integration of STEM approaches with Project-Based Learning (PjBL) and educational robotics has emerged as one of the most dominant trends in science and physics education research over the past five years. Syntheses of multiple systematic literature reviews and meta-analyses indicate that the combination of these three elements creates authentic, contextual, and real-world problem-oriented learning environments. Roslina and Samsudin (2022), through a systematic review of STEM–PjBL-based physics learning, confirmed that this model consistently produces positive effects on students' science process skills and problem-solving abilities compared to conventional instruction.

Within the STEM context, PjBL positions projects as the core of learning activities, where students are confronted with complex problems requiring the integration of science, technology, engineering, and mathematics to produce concrete solutions. Chistyakov et al. (2023) identified key characteristics of effective PjBL in science education, including authentic problems, in-depth investigation, tangible products, and continuous reflection. When integrated with STEM, projects function not only as vehicles for concept demonstration but also as platforms for developing scientific skills, from problem formulation to data-based solution evaluation.

Educational robotics serves as a project artifact that bridges conceptual and practical dimensions within STEM–PjBL. Robots allow students to apply physics principles directly through processes of design, assembly, programming, and system testing. Uslu et al. (2023), in their systematic review, emphasized that the use of robots in science learning promotes engagement in higher-order thinking activities, particularly in problem-solving and science process skills. The iterative nature of robot development, testing, identifying errors, and refining designs, closely aligns with the stages of the scientific method that form the core of physics learning.

Moreover, several studies demonstrate that the integration of robotics within STEM–PjBL has a significant impact on the development of problem-solving abilities. Wang et al. (2023), through a meta-analysis, found that educational robotics positively affects problem-solving, collaboration, and learning motivation. These findings are reinforced by Sapounidis et al. (2024), who concluded that robotics–STEM activities statistically enhance students' executive skills, including planning, spatial reasoning, and problem-solving. In physics learning, these skills are essential for understanding variable relationships, modeling physical systems, and interpreting experimental results.

Science process skills, such as observing, measuring, classifying, formulating hypotheses, analyzing data, and drawing conclusions, also show consistent improvement in STEM–PjBL- and robotics-based learning environments. Arafat et al. (2024) reported that educational robotics within integrated STEM frameworks provides opportunities for students to develop inquiry skills through independent exploration and experimentation. This is further supported by Amalina and Vidákovich (2022), who emphasized that the integration of engineering and technology serves as a key connector in interdisciplinary STEM problem-solving assessment.

Despite these benefits, the literature also identifies several limitations in the implementation of robotics-based STEM–PjBL. Many studies continue to focus on general learning outcomes or attitudes toward STEM, without providing detailed explanations of how science process skills and problem-solving abilities are developed through project and media design. In addition, robots used in many studies are often generic and not specifically designed to support physics experiments involving quantitative measurement (Lotriet & Gouws, 2025). As a result, the potential of robotics as a physics learning medium emphasizing data analysis and empirical validation remains underutilized.

In this context, the integration of STEM, PjBL, and robotics should be understood not only as a pedagogical strategy, but as a comprehensive learning design framework that requires alignment among learning objectives, activities, media, and assessment. The robotics developed must be capable of facilitating systematic project stages, ranging from physics problem identification and solution design based on scientific principles to result evaluation through experimental data. Through this approach, robotics-based STEM–PjBL has strong potential to support the simultaneous and sustainable development of science process skills and problem-solving abilities in physics education.

**Research Gap and Novelty Position of STEM-Integrated ESP32-Based Robotic Learning Media**

Recent literature reviews indicate that the integration of STEM, educational robotics, and Project-Based Learning (PjBL) has been widely implemented in science and physics education. Numerous systematic reviews and meta-analyses report that these approaches have positive effects on learning outcomes, attitudes toward STEM, and the development of higher-order thinking skills, particularly problem-solving abilities and science process skills (Ouyang & Xu, 2024; Wang et al., 2023; Roslina & Samsudin, 2022). However, as summarized in Table 1, most existing studies still emphasize the general effectiveness of instructional approaches and have not sufficiently focused on developing physics learning media that are specifically designed to reflect the characteristics of physics as a data-driven experimental science.

From a disciplinary perspective, Table 1 shows that physics is frequently mentioned in STEM and educational robotics research, yet its role remains relatively limited compared to technology-focused or interdisciplinary studies. Several studies indicate that physics is often used merely as an application context rather than as a central focus in learning media design and assessment (Lotriet & Gouws, 2025; Wang et al., 2024). As a result, essential aspects of physics learning, such as controlled experimentation, quantitative measurement, sensor-based data collection, and analysis of relationships among variables, have not been fully integrated into the design of existing educational robots.

From a technological perspective, the ESP32 platform and IoT technologies are widely recommended for STEM education due to their low cost, flexibility, and open-source nature (Abichandani et al., 2022; Kalaitzidou & Pachidis, 2023). Nevertheless, as shown in Table 1, the use of ESP32 in educational settings is still predominantly oriented toward programming instruction, robotic literacy, or general IoT applications. Studies that develop ESP32 as an experimental physics learning medium, particularly for fostering science process skills through real-time sensor data acquisition and analysis, remain very limited (Karalekas et al., 2023).

In addition, from pedagogical and assessment perspectives, many STEM–PjBL and educational robotics studies place greater emphasis on learning outcomes or increases in student motivation, without explicitly linking learning media design to indicators of physics-specific science process skills. Amalina and Vidákovich (2022) emphasize that the integration of engineering and technology plays an important role in STEM problem-solving assessment; however, Table 1 indicates that studies explicitly connecting robotic media design with assessment instruments for physics science process skills and problem-solving abilities are still scarce. This condition highlights the need for a more structured, competency-oriented approach.

**Table 1.** Research Map of STEM-Integrated ESP32-Based Robotic Learning Media Development

| Author (Year) | Main Research Findings | Limitations / Research Gaps |
|---|---|---|
| Tassilova et al. (2025) | Technology integration in STEM significantly improves problem-solving and 21st-century skills | Technology-based physics learning media have not been specifically developed |
| Abichandani et al. (2022) | ESP-based IoT devices effectively support STEM learning | The use of ESP as physics learning media has not been explored |
| Sherwani & Asad (2023) | Educational robotics increases student engagement and critical thinking | Robotic designs for physics learning are not clearly specified |
| Karalekas et al. (2023) | ESP32 is suitable for use in educational robotics | Focus is on machine learning rather than physics or science process skills |
| Roslina & Samsudin (2022) | STEM–PjBL is effective in improving physics science process skills and problem-solving | Physics robotic learning media are not yet systematically designed |
| Musengimana et al. (2025) | Problem-solving is a core competency in physics learning | Technology-based and experimental approaches remain limited |
| Pinar et al. (2025) | STEM contexts enhance scientific creativity and problem-solving | Physics learning media are not the primary focus |
| Pacala et al. (2025) | ESP32 supports computational thinking and robotic literacy | Focus is on teacher development rather than students |
| Kalaitzidou & Pachidis (2023) | ESP32 is a commonly used platform in educational robotics | Science process skill outcomes are rarely examined |
| Ouyang & Xu (2024) | Educational robotics positively affects learning performance | Effectiveness in physics contexts is not yet optimal or contextualized |
| Sapounidis et al. (2024) | Robotics–STEM improves students' problem-solving skills | Physics-specific studies remain limited |
| Wang et al. (2023) | Educational robots enhance motivation and problem-solving ability | Design of physics robotic learning media is not discussed |
| Uslu et al. (2023) | Educational robotics improves science process skills and higher-order thinking skills | STEM integration is not explicitly designed |
| Wang et al. (2024) | Physical robots are used in science learning, including physics | STEM approaches and science process skill assessment are not optimal |
| Arafat et al. (2024) | STEM-integrated educational robotics improves problem-solving and critical thinking | Physics experiment-based learning media have not been developed |
| Lotriet & Gouws (2025) | Robotics positively affects physics understanding and problem-solving | The use of ESP32 and IoT is not addressed |
| Ghashim & Arshad (2023) | IoT improves learning outcomes and learning experiences | IoT implementation in school physics remains rare |
| Seckin-Kapucu (2023) | Robotic coding improves science process skills and problem-solving | STEM integration is not fully implemented |
| Astuti et al. (2021) | STEM-based learning improves physics problem-solving | STEM-based robotic learning media have not been developed |
| Darmawansah et al. (2023) | Robotics–STEM effectively develops 21st-century skills | Experimental physics is not the main focus |

Based on these identified gaps, the development of STEM-integrated ESP32-based robotic physics learning media occupies a clear and scientifically relevant position of novelty. This study does not merely adopt established STEM–PjBL and educational robotics approaches, but applies them specifically within an experimental and data-driven physics context. By positioning the ESP32 as the core of the robotic system, the developed learning media have the potential to integrate physics theory, experimental activities, and the development of science process skills and problem-solving abilities in a coherent manner.

Consequently, this study offers both conceptual and practical contributions to the advancement of contextual and future-oriented STEM-based physics education aligned with the demands of 21st-century learning.

This study is important because it addresses a critical gap between the rapid advancement of low-cost IoT-based technologies and their pedagogically grounded application in physics education. While ESP32-based systems offer significant potential for enabling real-time data acquisition, experimentation, and contextual learning, their integration into structured STEM physics learning environments remains limited and under-theorized. By systematically mapping the current state of the art, this research provides a foundational understanding of how technological affordances can be aligned with pedagogical objectives and physics content to enhance science process skills and problem-solving abilities. Therefore, this study contributes not only to the body of knowledge in STEM education but also serves as a strategic reference for designing more effective, technology-enhanced physics learning media.

Furthermore, this study opens several directions for future research. Empirical studies are needed to develop and validate ESP32-based robotic learning media that explicitly integrate physics concepts with measurable indicators of science process skills and problem-solving performance. Future research should also explore experimental and quasi-experimental designs to evaluate the effectiveness of such media across different educational levels and contexts. In addition, interdisciplinary approaches that combine learning analytics, IoT data visualization, and adaptive learning systems could further enhance the impact of robotics-based STEM learning. Thus, continued research is essential to bridge the gap between technological innovation and meaningful pedagogical implementation in 21st-century physics education.

### Limitation and Future Work

These findings highlight the importance of this research in bridging the gap between technological innovation and pedagogically meaningful physics learning. By providing a structured mapping of current studies, this research offers a conceptual foundation for developing STEM-integrated ESP32-based robotic learning media that are both technologically feasible and pedagogically relevant. Furthermore, future research should focus on the design and development of such media, followed by empirical validation through experimental or quasi-experimental studies across diverse educational contexts. Additional investigations are also recommended to integrate learning analytics, IoT-based data visualization, and adaptive learning systems to enhance learning effectiveness and scalability. Through these efforts, future studies can contribute to a more coherent integration of technology, pedagogy, and physics content in advancing 21st-century physics education.

## CONCLUSION

This study systematically mapped research developments, potential, and gaps related to the integration of STEM approaches, Project-Based Learning (PjBL), and educational robotics in physics education, with a specific focus on ESP32-based technology. In terms of research developments, the literature demonstrates a consistent increase in the use of robotics-enhanced STEM learning to support 21st-century competencies. Previous studies confirm that such approaches effectively improve higher-order thinking skills, particularly science process skills and problem-solving abilities, through authentic, inquiry-based, and data-driven learning experiences. Regarding research potential, ESP32 emerges as a promising platform due to its capability for real-time data acquisition, wireless connectivity, and compatibility with various sensors, making it highly suitable for supporting quantitative experimentation in physics learning. However, this review also identifies a significant research gap: most existing studies focus on general robotics or programming contexts, with limited attention to the systematic design of ESP32-based robotic media that explicitly align with physics concepts, experimental data analysis, and structured indicators of science process skills and problem-solving.

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