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Integrating Project-Based Learning and the Internet of Things in vocational education: A literature review of developments, implementation, and future prospects for 21st-century learning

Muhammad Naufal Fadhlurrohman[1], Hartoyo[2]

[1 2] Universitas Negeri Yogyakarta, Yogyakarta, Indonesia

*Corresponding Author: naufalfadhlurrohman.m06@gmail.com

Abstract

Digital transformation and the advancement of Industry 4.0 technologies require vocational education to develop technical competencies and 21st-century skills through industry-relevant learning. This study aims to analyze the integration of Project-Based Learning (PjBL) with the Internet of Things (IoT) as a learning approach to strengthen vocational competencies and institutional readiness for technological change. This qualitative study employed a literature review of 14 academic documents published between 2019 and 2026, using content analysis and thematic synthesis. The findings indicate that PjBL–IoT integration is grounded in constructivism, social learning theory, and Technology-Enhanced Learning, and is implemented through IoT technological architecture and six project-based learning stages. This approach has the potential to support the development of 4C competencies, computational thinking, technical skills, and technological literacy. This study contributes an integrated perspective linking pedagogy, technology, competency development, and educational governance, highlighting POAC-based management, TPACK development, data security, and industry partnerships as essential conditions for sustainable implementation.

Keywords: Project-Based Learning; Internet of Things; Vocational education; 4C competencies; Computational thinking.

Abstrak

Transformasi digital dan perkembangan teknologi Industri 4.0 menuntut pendidikan vokasi untuk mengembangkan kompetensi teknis serta keterampilan abad ke-21 melalui pembelajaran yang relevan dengan kebutuhan industri. Penelitian ini bertujuan menganalisis integrasi *Project-Based Learning* (PjBL) bermuatan *Internet of Things* (IoT) sebagai pendekatan pembelajaran untuk memperkuat kompetensi dan kesiapan pendidikan vokasi dalam menghadapi perubahan teknologi. Penelitian ini menggunakan pendekatan kualitatif melalui kajian literatur terhadap 14 dokumen akademik yang diterbitkan pada periode 2019–2026, dengan teknik analisis isi dan sintesis tematik. Hasil kajian menunjukkan bahwa integrasi PjBL–IoT berlandaskan konstruktivisme, teori pembelajaran sosial, dan *Technology-Enhanced Learning*, serta diimplementasikan melalui arsitektur teknologi IoT dan enam tahapan pembelajaran berbasis proyek. Pendekatan ini berpotensi mendukung pengembangan kompetensi 4C, *Computational Thinking*, keterampilan teknis, dan literasi teknologi. Kontribusi kajian ini terletak pada pemetaan keterkaitan antara pedagogi, teknologi, capaian kompetensi, dan tata kelola pendidikan melalui POAC, penguatan TPACK, keamanan data, serta kemitraan industri sebagai prasyarat keberlanjutan implementasi.

Kata Kunci: *Project-Based Learning*; *Internet of Things*; Pendidikan vokasi; Kompetensi 4C; *Computational Thinking*.

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Introduction

Changes in workforce demands in the Industry 4.0 era require vocational education to prepare graduates who not only possess specific job-related skills but are also capable of adapting to new technologies and evolving work practices. Through interviews with 10 industry experts conducted in two meetings, Chou et al. (2018) found that technical and vocational education curricula need to incorporate big data, cloud computing, and the Internet of Things (IoT), while also strengthening practical classes and school–industry partnerships. Hadromi et al. (2019) identified that vocational high school graduates require both technical skills and employability skills, including proficiency in information technology, operational technology, IoT, and big data analytics. They also emphasized data, technological, and human literacy as essential competencies for addressing the integration of the physical, digital, and human worlds. These findings position IoT as a competency that needs to be incorporated into vocational learning.

However, adapting vocational education requires more than simply adding new subjects or technological devices without transforming learning governance. In a conceptual study of vocational education in Indonesia, Samani (2018) proposed shifting the focus from competencies to capabilities through modular and integrative curricula to enable graduates to adapt to changing work practices. Nevertheless, through development research conducted at a vocational high school using interviews, observations, and documentation, Subagyo et al. (2018) found that the implementation of an IoT-based curriculum had not been fully realized: planning was not oriented toward specific targets, implementation tended to be spontaneous, and evaluation findings were not followed up through reflective documentation. These findings reveal a gap between the demands of digital transformation and schools' readiness to translate them into well-planned learning practices. This gap is both pedagogical and institutional in nature.

Project-Based Learning (PjBL) is relevant to addressing these demands because it uses projects and products as contexts for applying knowledge. Sukamta et al. (2018) explained that PjBL has the potential to foster product-oriented creativity, independence, responsibility, attendance, and higher-order thinking. They also emphasized several prerequisites, including time management, appropriate material selection, and teacher readiness. Through a systematic literature review of PjBL in vocational education, Megayanti et al. (2020) identified evidence supporting the development of critical thinking, problem-solving, communication, collaboration, and creativity. However, they also noted that teachers, students, equipment, and the learning environment could act as limiting factors. In IoT projects, these principles can be implemented through the design, assembly, programming, and testing of systems that generate measurable solutions to real-world problems. Thus, PjBL offers an active

learning mechanism that connects vocational tasks with the process of developing solutions, although its effectiveness depends on the quality of instructional design and the availability of adequate facilities.

Previous studies have examined individual components of this approach, but have not always brought them together within a unified learning design. Susanti and Trisusana (2018) investigated students from two vocational high schools in urban and rural areas. Through focus group discussions, interviews, and observations, they reported improvements in literacy skills following the implementation of PjBL in English language learning. Ardiyono et al. (2019) discussed a PjBL-based milling machine module for vocational high schools; however, their study relied on a literature review rather than an implementation experiment. Meanwhile, Subagyo et al. (2018) highlighted the suboptimal planning, implementation, and evaluation of IoT-based curricula in vocational high schools. Megayanti et al. (2020) synthesized the benefits of PjBL for developing 21st-century competencies but did not specifically examine its integration with IoT. Accordingly, further research is needed to establish connections among project-based pedagogy, IoT technology, competencies, and vocational education governance.

In response to this research gap, this study aims to analyze and synthesize the literature on the implementation of IoT-integrated PjBL in vocational education. Specifically, it maps the pedagogical foundations of PjBL–IoT integration, the technological architecture and stages of its learning implementation, its reported contributions to 21st-century competencies, and the governance requirements and sustainability strategies involved. The significance of this review lies in the need for an understanding that connects pedagogical, technical, and institutional dimensions, since the success of a project is determined not only by whether a prototype functions but also by the quality of the learning process, educator readiness, facility availability, data security, and the relevance of projects to the world of work. This study is expected to produce a conceptual framework and evidence-based recommendations while distinguishing findings that directly examine PjBL–IoT integration from supporting findings that address PjBL or IoT separately.

Method

This study adopts a qualitative approach using a literature review method to analyze the implementation of Project-Based Learning (PjBL) integrated with the Internet of Things (IoT) in vocational education. The analysis employs content analysis and thematic synthesis, enabling findings from various types of documents to be compared in terms of their focus, methods, contexts, technologies, and learning outcomes. The review covers 14 academic documents published between 2019 and 2026, including research and development (R&D) studies, quasi-experimental studies, systematic literature reviews and bibliometric analyses, community service reports, and a

master's thesis in technology and vocational education. This diversity of documents is maintained because the review examines not only learning effectiveness but also pedagogical foundations, technological design, educator readiness, and implementation governance. The reporting of the literature identification and selection process follows PRISMA 2020 (Page et al., 2021), with PRISMA treated as a reporting guideline rather than an analytical technique.

The search strategy was designed to cover Google Scholar, GARUDA, and the Directory of Open Access Journals (DOAJ), with a publication period spanning 2019–2026 and publications in Indonesian and English. The search terms were developed from four conceptual groups: "*Project-Based Learning*" OR "*Project Based Learning*" OR *PjBL*; "*Internet of Things*" OR *IoT*; "*Vocational Education*" OR *TVET* OR *SMK* OR "*Vocational High School*"; and "*21st Century Skills*" OR *4C* OR "*Computational Thinking*" OR "*Problem Solving*". Boolean combinations linked the PjBL and IoT groups to the vocational education context, while supplementary searches connected either PjBL or IoT with 21st-century competencies. Literature was included if it was relevant to learning, technology, or competencies in vocational education and its full text was available for examination. Documents were excluded if they fell outside the specified publication period, were irrelevant, lacked sufficient methodological information, or did not belong to the designated source types. The search strategy was reported with consideration of the transparency principles outlined in PRISMA-S (Rethlefsen et al., 2021).

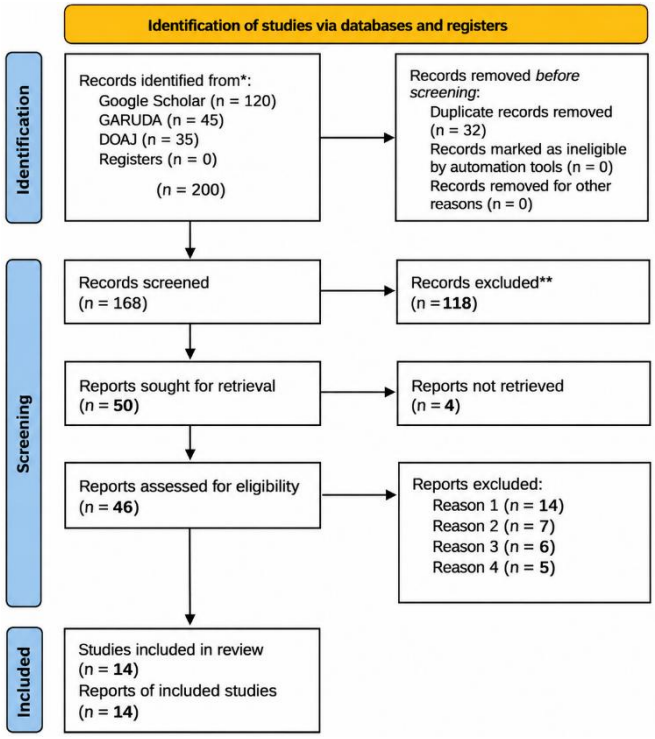

Figure 1. PRISMA 2020 flow diagram of the literature selection process

Source: Adapted from Page et al. (2021)

The literature selection process was structured around five stages: identification, duplicate removal, title and abstract screening, full-text assessment, and final inclusion. For reporting practice, the flow diagram uses simulated figures: 200 records were identified (Google Scholar: 120, GARUDA: 45, and DOAJ: 35), 32 duplicates were removed, 168 records were screened, and 118 were excluded. A total of 50 reports were sought for retrieval, four could not be retrieved, and 46 were assessed for eligibility. Full-text assessment resulted in the exclusion of 32 documents due to irrelevant focus (14), unsuitable context (7), insufficient data (6), or inappropriate document type (5), leaving 14 documents for inclusion. This selection process is presented in Figure 1. Data from each document were extracted into a matrix recording the authors, year, objectives, methods, participants, technologies, pedagogical models, findings, and limitations. The findings were subsequently coded and synthesized into four themes: pedagogical foundations, learning architecture and design, 21st-century competencies, and governance and sustainability. The recording of the numbers of records, reports, and studies follows the explanations provided by Rethlefsen and Page (2022).

Results and Discussion

Mapping and synthesis of literature findings on PjBL–IoT integration in vocational education

Based on the mapping of 14 relevant studies, the literature on Project-Based Learning (PjBL), the Internet of Things (IoT), and vocational education reveals diverse developments in terms of methodological approaches, educational contexts, and research focuses. The literature analyzed encompasses research and development (R&D) studies, quasi-experimental studies, literature reviews, document analyses, and training and community service activities at the secondary and higher education levels. In general, these studies can be classified into several major areas: the development of project-based learning media and models, the use of digital technology in education, the implementation of IoT technology in learning activities, the development of 21st-century competencies, and the strengthening of vocational education governance. This diversity of approaches indicates that technology integration in vocational education is not merely concerned with the use of digital devices but also involves pedagogical design, student competency development, and institutional readiness to support technology-based learning.

Table 1. Mapping and synthesis of literature on PjBL, IoT, and vocational education

Authors (Year)	Research focus and methods	Main findings	Relevance to the review
Sarwandi (2019)	Development research using the 4-D model to produce a mobile-based PjBL e-module	Content validity was 0.83 and media validity was 0.87; lecturer and student	Supports the development of learning media and

	for a Project Management course in vocational education.	practicality scores were 89 and 86, respectively; the gain score was 0.44 (moderate category).	the application of PjBL in vocational education.
Arpan et al. (2024)	Training and focus group discussions (FGDs) on the application of IoT to develop the smart school concept at SMA Negeri II Binjai.	IoT was introduced to support automated classroom management, real-time attendance monitoring, and interactive learning.	Provides an overview of IoT applications in educational environments.
Malay et al. (2025)	Qualitative study based on document analysis of technology use in school and university environments.	Digital learning platforms, learning management systems (LMSs), simulations, and AI technologies support learning flexibility and participation but face infrastructure and educator competency constraints.	Supports the rationale for using technology in learning.
Rosa et al. (2025)	Systematic literature review and bibliometric analysis of PjBL in IoT projects and the development of computational thinking (CT) and collaboration.	The integration of PjBL and IoT projects has the potential to develop CT and collaboration, but studies combining PjBL, IoT, and both competencies in an integrated manner remain limited.	Provides a direct foundation for identifying the research gap in PjBL–IoT integration.
Arifin et al. (2025)	Literature review of ICT-based learning models in response to the Society 5.0 era.	Technology-based learning models support the development of 4C skills, but their implementation faces challenges related to teacher readiness, resistance to change, and limited equipment.	Supports the foundation for digital learning and 21st-century competencies.
Utari and Aprison (2025)	Systematic literature review with thematic synthesis of 129 articles on the integration of constructivism and AI.	AI has the potential to serve as a cognitive partner by providing learning support through scaffolding, metacognitive reflection, and the development of 21st-century competencies.	Supports the theoretical foundation of technology-enhanced learning and constructivism.

Ridho et al. (2025)	Training and hands-on practice in IoT-based smart systems for students in the Computer Network and Telecommunications Engineering program at SMK Negeri 2 Padang.	Training involving Arduino, ESP32/ESP8266, sensors, Blynk, and Telegram supported the acquisition of control logic and remote device monitoring skills.	Provides evidence of IoT implementation and technical skill development among vocational high school students.
Tisna et al. (2026)	IoT training using a learning-by-doing approach for students at SMK Pembangunan Kikil Pacitan.	The students' minimum score increased from 60 to 80, while responses to the training indicated an average Likert score above 4.5.	Supports the development of IoT literacy and technical skills through hands-on practice.
Damayanti et al. (2025)	Interactive training and hands-on practice in Node-RED-based IoT for teachers and laboratory assistants at SMK Negeri 5 Banjarmasin.	A total of 86% of participants considered the topic highly relevant, 95% rated the learning media as highly supportive, and 55% reported readiness to apply the technology in learning.	Demonstrates the importance of educator readiness and competency development in IoT implementation.
Dhurohman and Kurniawan (2026)	Quasi-experimental study on the implementation of PjBL in the Creative Products and Entrepreneurship subject at SMKN 5 Surabaya.	The experimental class achieved higher mean scores across all 4C dimensions, but statistical testing indicated no statistically significant difference ($p = 0.753$). The study also reported a Cohen's d of 1.459.	Provides supporting evidence regarding the relationship between PjBL and 4C competencies but does not examine IoT integration.
Amarudin et al. (2026)	Implementation of PjBL assisted by the Tinkercad simulator in IoT learning among Grade XII students at MA Nurul Ummah Yogyakarta.	The project completion rate was reported at 70.59%; the temperature sensor project achieved 100%, and 69.23% of students obtained a post-test score of 100.	Provides direct empirical evidence of PjBL and IoT integration.
Sudrajat et al. (2026)	Literature review on optimizing PjBL in vocational education from an educational management perspective.	Optimizing PjBL requires planning based on industry competencies, resource management, the implementation of authentic projects, and continuous evaluation.	Supports the management and governance dimensions of vocational learning.

Kholil et al. (2026)	Development research using the ADDIE model to produce an IoT module incorporating PjBL learning syntax for students in the Physics Education program at Universitas Jambi.	Material expert validation reached 88.5% and media expert validation reached 91.2%; the development study also reported high student collaboration outcomes.	Provides direct empirical evidence of the development of PjBL–IoT-integrated learning materials.
Susmanto et al. (2026)	Community service based on a learning-by-doing approach through the implementation of IoT-based smart systems among 50 students at SMK Negeri 5 Telkom Banda Aceh.	The mean score increased from 75.4 to 85.6, representing a 13.53% increase; 75% of participants were able to assemble, program, test, and troubleshoot smart systems.	Supports the development of technological literacy and practical IoT skills in vocational education.

Source: Compiled by the authors based on the 14 studies reviewed.

Based on the mapping presented in Table 1, the first group of studies focuses on developing pedagogical foundations, learning models, and the use of educational technology. Through development research using the 4-D model, Sarwandi (2019) developed a mobile-based e-module incorporating PjBL for a Project Management course at Universitas Negeri Padang. The study indicated that project-based instructional material development could produce valid and practical learning media, with learning gains in the moderate category. From a broader perspective, Malay et al. (2025) examined the use of educational technology in school and university environments, particularly learning management systems (LMSs), digital simulations, and artificial intelligence technologies.

Meanwhile, Arifin et al. (2025) identified various ICT-based learning models relevant to the Society 5.0 era, including blended learning, flipped classrooms, PjBL, and simulation-based learning. Utari and Aprison (2025) complemented these perspectives through a synthesis of 129 articles examining the relationship between constructivism and AI in the development of 21st-century competencies. In the context of vocational education, Sudrajat et al. (2026) specifically emphasized that PjBL implementation needs to be supported by educational management functions encompassing competency-based planning, resource organization, the implementation of authentic projects, and continuous evaluation. Overall, this group of studies underscores that the use of educational technology requires alignment among pedagogical models, learning media, educator competencies, and institutional governance.

The next group of studies focuses on the application of IoT technology in educational environments, particularly through training activities, hands-on practice, and smart system development. Arpan et al. (2024) introduced the use of IoT to support the smart school concept at SMA Negeri II Binjai, particularly in automated classroom

management, real-time student attendance monitoring, and the development of interactive learning devices. In the vocational education context, Ridho et al. (2025) conducted smart system training for students in the Computer Network and Telecommunications Engineering program at SMK Negeri 2 Padang using Arduino Uno, ESP32/ESP8266, sensors, and the Blynk and Telegram applications.

Tisna et al. (2026) implemented a learning-by-doing approach through IoT introductory activities and hands-on practice using ESP32, sensors, actuators, and the Arduino IDE among students at SMK Pembangunan Kikil Pacitan. From the educator perspective, Damayanti et al. (2025) organized Node-RED-based IoT training for teachers and laboratory assistants at SMK Negeri 5 Banjarmasin to improve their ability to design real-time control and monitoring systems. Meanwhile, Susmanto et al. (2026) implemented IoT-based smart systems through assembly, programming, testing, and troubleshooting activities involving students at SMK Negeri 5 Telkom Banda Aceh. Although these studies provide insights into the use of IoT technology in vocational learning, their primary focus remains on technology introduction, device proficiency, and practical skill development. They have not all incorporated IoT as part of a systematic PjBL pedagogical design.

Studies that more directly connect PjBL and IoT technology include those by Rosa et al. (2025), Amarudin et al. (2026), and Kholil et al. (2026). Through a systematic literature review and bibliometric analysis, Rosa et al. (2025) examined the application of PjBL in IoT projects and its relationship with the development of computational thinking and collaboration. Their review identified that Arduino-, Scratch-, and educational robotics-based projects within a PjBL framework have the potential to strengthen students' computational thinking and collaborative abilities, although studies integrating all these aspects within a unified learning system remain limited.

At the implementation level, Amarudin et al. (2026) applied PjBL assisted by the Tinkercad simulator in IoT learning among Grade XII students at MA Nurul Ummah Yogyakarta. The projects involved developing a seven-segment-based traffic light, a light sensor, a temperature sensor, and a running text display. Furthermore, Kholil et al. (2026) developed an IoT-based learning module incorporating PjBL syntax for air quality topics among students in the Physics Education program at Universitas Jambi. The module used NodeMCU, environmental sensors, an OLED display, and the Blynk application as learning components. These three studies demonstrate that PjBL–IoT integration has begun to develop through systematic reviews, simulation-assisted project implementation, and instructional material development. Nevertheless, each study differs in its focus, educational level, and form of implementation.

In terms of learning outcomes, the reviewed literature indicates several positive developments in knowledge acquisition, technical skills, collaboration, problem-solving, and students' technological literacy. For example, Tisna et al. (2026) reported

that students' minimum scores increased from 60 to 80 following hands-on IoT training, accompanied by positive responses to the learning activities, with an average Likert score above 4.5. Susmanto et al. (2026) also reported an increase in participants' mean scores from 75.4 to 85.6 following IoT-based smart system implementation activities, with 75% of participants able to complete the stages of assembly, basic programming, testing, and troubleshooting. In the implementation of Tinkercad-assisted PjBL, Amarudin et al. (2026) reported a project completion rate of 70.59% and high post-test performance among the participants.

Meanwhile, Kholil et al. (2026) demonstrated the feasibility of the PjBL–IoT module based on material expert validation of 88.5% and media expert validation of 91.2%, while also reporting high student collaboration outcomes. Dhurohman and Kurniawan (2026), in turn, found that the experimental class achieved higher mean scores than the control class in the dimensions of critical thinking, creativity, communication, and collaboration. However, the statistical testing results showed a significance value of 0.753, indicating that the difference between the groups could not be considered statistically significant. This finding highlights the importance of distinguishing between trends in improved outcomes, effect sizes, and statistical significance when interpreting the contributions of a learning model. Thus, the available empirical evidence indicates the potential of PjBL and IoT to support vocational competencies, although the strength of such conclusions remains dependent on the research design, measurement instruments, and implementation context of each study.

Overall, the mapping of the 14 studies indicates that research on PjBL, IoT applications, educational technology, and the development of 21st-century competencies has advanced through various research approaches. However, the pedagogical, technological, and competency development dimensions have not yet been fully examined in an integrated manner. Some studies emphasize PjBL implementation without integrating IoT devices, whereas others focus on IoT training and device utilization without systematically elaborating a project-based learning design. Indeed, Rosa et al. (2025) explicitly identified the limited number of studies connecting PjBL, IoT, computational thinking, and collaboration within a comprehensive learning framework.

Studies by Amarudin et al. (2026) and Kholil et al. (2026) have provided examples of direct implementation through simulation-assisted projects and instructional module development, respectively, but differ in their contexts and scope. Furthermore, educator readiness, infrastructure limitations, facility management, data security, and the alignment of projects with industry needs require further attention. Therefore, a more comprehensive discussion of pedagogical foundations, technological architecture, implementation syntax, competency outcomes, and educational

governance is needed to explain how PjBL–IoT integration can be systematically developed as a learning approach in 21st-century vocational education.

Pedagogical foundations and implementation design of PjBL–IoT in vocational education

The integration of Project-Based Learning (PjBL) and the Internet of Things (IoT) should be understood as the convergence of pedagogical design and technological environments, rather than merely the use of digital devices in classroom projects. PjBL positions authentic problems, inquiry, and products as the driving forces of learning. Thomas (2000) emphasized that projects should be central to the curriculum, guided by meaningful questions, involve constructive investigation, provide learners with autonomy, and relate to real-world situations. Krajcik and Blumenfeld (2006) also highlighted driving questions, inquiry, collaboration, and artifacts that represent learners' understanding. IoT complements this framework through sensors, actuators, connectivity, and data exchange among devices (Atzori et al., 2010). In vocational education, Bunyamin (2023) examined PjBL–IoT in the SMK Membangun Desa program and reported achievement levels of 69% for vocational skill development, 73% for connecting theory with practice, and 74% for collaborative learning in solving contextual problems. Thus, technology serves as a medium for creating solutions rather than as the learning objective itself.

The constructivist foundation explains why the experience of designing and testing IoT devices can facilitate meaningful learning. Piaget (1952) explained knowledge development through assimilation, which involves incorporating new experiences into existing schemas, and accommodation, which involves modifying schemas when new experiences do not align with prior understanding. When a sensor produces readings that differ from expectations, learners need to reconsider their assumptions, circuitry, or programming logic; this process provides an opportunity to adjust their understanding. Vygotsky (1978) extended this explanation through the concept of the Zone of Proximal Development (ZPD), defined as the distance between what learners can achieve independently and what they can achieve with the assistance of others. Accordingly, project tasks should be structured progressively and accompanied by support from teachers or more competent peers. PjBL–IoT has pedagogical value when practical activities generate thinking processes, rather than merely producing technically functional products that are subsequently subjected to reflection.

The social dimension of IoT learning can be explained through Bandura's social learning theory and research on guidance in problem-solving. Bandura (1977) explained that individuals learn through observing models, processing information, and considering the consequences of actions; learners do not have to acquire all skills solely through their own trial and error. In IoT projects, teachers can demonstrate safety procedures, assembly techniques, or error diagnosis, after which learners

observe and practice these procedures. Wood, Bruner, and Ross (1976) demonstrated how tutors assist learners in completing tasks that initially exceed their independent capabilities. This idea provides an important foundation for scaffolding: assistance is provided according to the level of difficulty and gradually withdrawn as learners' abilities improve. The implication is that group work does not automatically result in collaboration or social learning. Teachers need to design role distribution, demonstrations, feedback, and opportunities for learners to explain concepts to one another. Through such arrangements, social interaction becomes an integral part of conceptual understanding and technical skill acquisition.

The use of technology in PjBL–IoT should be situated within the framework of Technology-Enhanced Learning (TEL), which refers to the use of technology to support learning objectives and activities. Through a critical review of TEL literature in higher education, Kirkwood and Price (2014) cautioned that technology does not automatically improve learning; claims of improvement must be linked to pedagogical objectives and evidence of learning outcomes. Trilling and Fadel (2009) classified 21st-century skills into learning and innovation skills, digital literacy, and life and career skills. This framework is relevant to vocational education because IoT projects require problem-solving, creativity, communication, collaboration, and the responsible use of technology. Meanwhile, the Government of Japan defines Society 5.0 as a human-centered society that integrates cyberspace and physical space to harmonize economic development with the resolution of social problems (Cabinet Office, Government of Japan, n.d.). Therefore, the success of PjBL–IoT should be measured not by the sophistication of the devices but by the usefulness of the solutions and the quality of learning.

The technical architecture of IoT can be introduced to learners through the processes of sensing, processing, communication, and presentation or action. Atzori, Iera, and Morabito (2010) described IoT as an integration of identification, sensor and actuator networks, and communication protocols that enable objects to connect with one another. Gubbi et al. (2013) further highlighted the role of cloud computing and services in managing and utilizing data from distributed devices. More formally, the International Telecommunication Union (2012) recommendation, subsequently renumbered as Y.4000, outlines an IoT reference model comprising the device, network, service support and application support, and application layers; management and security aspects are also addressed. In learning projects, sensors such as the DHT22 or HC-SR04 capture physical conditions, microcontrollers process instructions, networks transmit data, and dashboards present information to users. The input–process–output scheme can facilitate instruction, but it should not be regarded as a complete technical architecture of IoT.

The selection of software and learning media should be guided by project objectives, learners' abilities, and the availability of facilities. Arduino IDE is used to write and upload programs to microcontrollers; Node-RED facilitates the visual configuration of data flows and dashboards; while Blynk or Telegram can serve as interfaces for monitoring and notifications. Protocols such as MQTT and HTTP regulate data exchange and therefore serve different functions from interface applications and programming tools. When physical devices are limited, simulators such as Tinkercad and visual programming languages can be used to test initial designs before assembly. Through a review of physical and virtual laboratories in science and engineering education, de Jong, Linn, and Zacharia (2013) demonstrated that the two offer different investigative experiences and can be combined. Therefore, simulation should serve as a bridge to authentic practice rather than as a permanent substitute for measuring, assembling, testing, and troubleshooting devices. E-modules can complement this process by providing guidance for independent learning.

To prevent learning from being limited to device assembly, PjBL–IoT should be implemented through stages that connect problems, inquiry, products, and reflection. Drawing on the characteristics of PjBL described by Thomas (2000) and Krajcik and Blumenfeld (2006), this review formulates an operational sequence consisting of six stages. First, contextual problem orientation, in which problems suitable for resolution through IoT are identified. Second, project planning, which involves formulating solutions, selecting components, assigning tasks, and establishing schedules. Third, experimentation and the assembly of sensors, microcontrollers, and actuators. Fourth, programming the system logic and integrating connectivity with networks or monitoring services. Fifth, system testing, data analysis, and troubleshooting to identify and correct errors. Sixth, product presentation, evaluation, and reflection on both the process and the outcomes. These six stages constitute an adaptation for IoT learning rather than a universal PjBL sequence; their order can be adjusted according to competencies, project requirements, available facilities, and learner characteristics.

Contributions, governance, and sustainability of PjBL–IoT implementation in vocational education

The integration of PjBL–IoT has the potential to expand the outcomes of vocational education beyond equipment proficiency toward the competencies required to design, test, and take responsibility for technological solutions. The available evidence indicates contributions in four areas: 4C competencies, computational thinking and problem-solving, mastery of knowledge and technical skills, and teacher readiness. However, the strength of the evidence varies. Kholil et al. (2026) developed a module that directly integrates PjBL and IoT, whereas Dhurohman and Kurniawan (2026) examined PjBL without IoT. In contrast, Tisna et al. (2026) and Susmanto et al. (2026) reported IoT training activities that were not entirely designed around PjBL. Therefore,

these findings need to be interpreted hierarchically: evidence of direct integration, evidence of PjBL, and evidence of IoT implementation. This distinction prevents the conclusion that all competency improvements are attributable solely to the PjBL–IoT model. Accordingly, this review does not assume that the effectiveness of each approach or educational level is equivalent.

Table 2. Synthesis of empirical contributions and implementation implications of PjBL–IoT in vocational education

Aspect	Supporting literature	Empirical findings	Implications
4C competencies	Dhurohman and Kurniawan (2026); Kholil et al. (2026); Sukerti and Susana (2018); Suningcih and Mardikantoro (2018)	The mean 4C scores in the PjBL class were descriptively higher; student collaboration in the PjBL–IoT module reached 85.50%; other PjBL studies reported improvements in writing skills.	Projects can provide opportunities to develop communication, collaboration, creativity, and critical thinking.
Computational thinking and problem-solving	Rosa et al. (2025); Susmanto et al. (2026); Ridho et al. (2025); Nurtanto et al. (2018)	The link strength between projects and collaboration was 237; observations of troubleshooting and programming reached 87%; more than 80% of Ridho's training participants completed the control logic module.	Device assembly, programming, and troubleshooting provide contexts for developing computational skills.
Cognitive mastery and technical skills	Tisna et al. (2026); Susmanto et al. (2026); Amarudin et al. (2026)	Tisna's scores increased from 80 to 96.5; Susmanto's scores increased from 75.4 to 85.6; Amarudin's project completion rate reached 70.59%.	IoT practice has the potential to support conceptual understanding and operational skills.
Teacher readiness	Damayanti et al. (2025); Hsu and Chen (2018); Arifin et al. (2025); Malay et al. (2025)	A total of 55% of teachers participating in Node-RED training were ready to implement it in their classrooms; Hsu and Chen mapped TPACK among 333 vocational teachers.	Teacher competency development needs to be aligned with technological, pedagogical, and content-related requirements.
Educational governance	Sudrajat et al. (2026); Terry and Rue (2010)	Sudrajat's review analyzed 28 articles and developed a framework for optimizing PjBL based on POAC.	Planning, organizing, implementation, and evaluation need to be integrated into a unified management system.

Security and sustainability	Arpan et al. (2024); Akeju et al. (2018); Bunyamin (2023); Sudrajat et al. (2026)	The literature identifies issues related to privacy, device security, program management, and the alignment of projects with industry needs.	Implementation requires data protection, institutional support, and industry partnerships.

Source: Compiled from the literature.

Contributions to 4C competencies are particularly evident in activities involving product design, role allocation, discussion, and presentation of results. Through a quasi-experimental study involving 65 vocational high school students, Dhurohman and Kurniawan (2026) reported higher mean scores in the PjBL class than in the control class for communication (2.44 versus 1.76), critical thinking (2.28 versus 1.39), creativity (2.12 versus 1.39), and collaboration (2.47 versus 1.45). However, the statistical test yielded $p = 0.753$, indicating that these differences were not statistically significant; the Cohen's d value of 1.549 reported by the authors needs to be verified because it is inconsistent with the results of the statistical test. Regarding direct integration, Kholil et al. (2026) reported a student collaboration score of 85.50%. Sukerti and Susana (2018) found improved writing outcomes among 64 vocational college students through the production of essays and infographics, while Suningcih and Mardikantoro (2018) reported that PjBL effectively improved vocational high school students' expository text writing skills ($t = 10.464$; $p < 0.01$) in Indonesian language learning.

PjBL–IoT also provides an authentic context for developing computational thinking and problem-solving because students must break down problems, identify data patterns, formulate algorithms, and trace the sources of system failures. Through a systematic literature review (SLR) and bibliometric analysis, Rosa et al. (2025) identified a strong relationship between the themes of projects and collaboration (link strength = 237), as well as between projects and the internet (134), while also highlighting the limited number of studies that fully integrate PjBL, IoT, and computational thinking (CT). Susmanto et al. (2026) reported observational achievement rates of 87% for troubleshooting and programming and 88% for system testing. Ridho et al. (2025) stated that more than 80% of participants completed the control logic and remote monitoring module. Although Nurtanto et al. (2018) examined Problem-Based Learning (PBL), rather than PjBL, they found improvements in critical thinking, group dynamics, motivation, and psychomotor skills of approximately 17%. Nurtanto's findings enrich the evidence on problem-based learning in vocational education but do not constitute evidence of PjBL–IoT.

Regarding cognitive mastery and technical skills, IoT training has demonstrated improvements in learning outcomes following instruction and hands-on practice. Tisna et al. (2026) reported that students' mean scores increased from 80 to 96.5, the

minimum score rose from 60 to 80, and the response scores for interest and motivation exceeded 4.5 on a five-point scale. Susmanto et al. (2026) recorded an increase in the mean score from 75.4 to 85.6, representing a 13.53% improvement; 75% of participants were able to assemble, program, test, and troubleshoot smart systems. In a PjBL activity supported by Tinkercad, Amarudin et al. (2026) reported that 70.59% of groups completed their projects and 69.23% of students obtained a post-test score of 100, although programming logic remained a challenge. Ridho et al. (2025) also reported that more than 80% of participants completed the control logic and remote monitoring module. These data provide empirical support for the potential of IoT practice but do not yet establish its long-term effects or the causal impact of PjBL–IoT.

The benefits of learning can only be sustained if schools manage it as a program rather than a one-time activity. After reviewing 28 out of 56 articles, Sudrajat et al. (2026) proposed a vocational PjBL management framework based on the functions of Planning, Organizing, Actuating, and Controlling (POAC). At the planning stage, the curriculum, projects, learning outcomes, time allocation, and the needs of the Business and Industrial World (DUDI) need to be aligned. Organizing involves laboratories, equipment, role allocation, teacher collaboration, and partnerships. Implementation requires teacher guidance, access to devices or simulators, and a learning culture that allows room for experimentation. Controlling is carried out through process monitoring and authentic assessment, such as performance rubrics, prototype portfolios, 4C assessments, and knowledge tests. This framework emphasizes that the quality of PjBL–IoT is determined not only by classroom activities but also by the consistency of institutional decisions and long-term support. Terry and Rue (2010) provides the conceptual basis for these four functions.

Three interrelated challenges need to be addressed: programming complexity, infrastructure inequality, and teacher readiness. Amarudin et al. (2026) reported a project success rate of only 33.33% for running-text projects, indicating the need for gradual training, beginning with simulation and visual programming before progressing to textual coding. Sarwandi (2019) developed a mobile e-module, while Tinkercad helps users test designs before using physical devices. Arifin et al. (2025) and Malay et al. (2025) identified limitations in equipment, the digital divide, and teacher competencies. Through a synthesis of 129 articles, Utari and Aprison (2025) positioned AI as a cognitive partner that provides scaffolding. Damayanti et al. (2025) reported that 55% of teachers participating in Node-RED training were ready to implement it in their classrooms. Through a survey of 333 vocational school teachers in Taiwan, Hsu and Chen (2018) found that age and seniority were associated with differences in pedagogical knowledge; not all background factors differentiated the dimensions of TPACK. Therefore, teacher development needs to be based on periodic needs assessments rather than assumptions that all educational institutions have identical requirements.

The sustainability of PjBL–IoT also requires security governance and meaningful connections with the world of work. Arpan et al. (2024) incorporated encryption and privacy into the introduction of smart school systems, while Akeju et al. (2018) identified risks involving network access, malware on servers and user devices, application vulnerabilities, and privacy in Bring Your Own Device (BYOD) and IoT programs in K–12 schools. They used the NIST Privacy Risk Management Framework to formulate risk management practices. Because IoT devices can collect environmental data as well as user identities, authentication, access restrictions, communication security, and data storage policies need to be designed from the outset. In terms of workplace relevance, Bunyamin (2023) and Sudrajat et al. (2026) emphasized the importance of contextual projects, competencies aligned with DUDI needs, and industry partnerships in the joint planning and evaluation of projects. Accordingly, prototypes need to address real-world problems rather than remain confined to laboratory assignments.

Conclusion

The findings indicate that the integration of Project-Based Learning (PjBL) and the Internet of Things (IoT) has strategic potential to strengthen the relevance of vocational education to the demands of 21st-century competencies. This finding is based on the relationship between project-based learning, hands-on technical experience, and authentic problem-solving, which enables students to develop cognitive, psychomotor, and social competencies in an integrated manner. This integration is important because procedural mastery of technology alone is insufficient to meet the increasingly complex demands of the workplace; students also need to develop critical thinking, creativity, communication, collaboration, and computational thinking skills. Operationally, this approach is implemented through six stages, beginning with problem identification, project planning, device assembly, programming and connectivity integration, testing and troubleshooting, and concluding with presentation and reflection. Thus, the principal value of PjBL–IoT lies in its ability to connect knowledge, technology, and practical problem-solving within a single contextualized learning experience.

This review makes a conceptual contribution by mapping the relationships among pedagogical foundations, technological architecture, competency outcomes, and implementation governance of PjBL–IoT in vocational education. However, this review has limitations because the analyzed literature varies in terms of research methods, educational levels, participant characteristics, and outcome indicators. Furthermore, not all studies directly examine the integration of PjBL and IoT. Some evidence focuses exclusively on PjBL or IoT implementation, meaning that generalizations regarding the effectiveness of their integration must be made with caution. Therefore, future research should develop a structured PjBL–IoT model and

empirically evaluate it through experimental or quasi-experimental designs with adequate implementation periods. Longitudinal studies are also needed to assess the sustainability of students' competencies, while model development should consider TPACK-based teacher readiness, equitable infrastructure provision, data security, and partnerships with the business and industrial sectors. These efforts are essential to ensure that PjBL–IoT does not remain merely a learning innovation but develops into a measurable, adaptive, and sustainable approach to vocational education.

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