



Development of an ESP32-Based Internet of Things Learning Model Integrating Multiple Approaches through Project-Based Learning

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Abstract: This study aims to develop an ESP32-based Internet of Things (IoT) instructional model that integrates multiple approaches within a Project-Based Learning (PjBL) framework and to evaluate its feasibility and effectiveness. The study employed a Research and Development (R&D) approach using the ADDIE model, with the implementation phase involving a one-group pretest–posttest design and 33 vocational high school students. The developed instructional model integrates PictoBlox as a block-based programming tool, C++ code conversion, Wokwi as a virtual laboratory, Arduino IDE, ESP32, and Blynk into a systematic instructional framework. Expert validation indicated that the instructional model was feasible for classroom implementation. The implementation results showed that the mean learning score increased from 70.00 on the pretest to 90.10 on the posttest. The Wilcoxon signed-rank test revealed a statistically significant difference between the pretest and posttest scores ($p < .001$), while the N-gain score was 0.44, indicating a moderate level of improvement. These findings suggest that the proposed ESP32-based IoT instructional model, which integrates multiple approaches within a Project-Based Learning framework, is feasible and has the potential to improve students' learning outcomes in vocational IoT education. The model also provides practical implications for vocational teachers by offering a systematic framework for IoT instruction, supporting vocational curriculum implementation, and providing a basis for adaptation to other vocational programs, such as electronics and electrical engineering.

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Introduction

The rapid advancement of the Internet of Things (IoT) has increased industrial demand for a workforce with competencies in embedded systems, computer networks, sensors, cloud computing, and microcontroller programming, making IoT one of the essential technological competencies in the Industry 4.0 and Society 5.0 era (Badshah et al., 2024; Fernández-Batanero et al., 2024). This development presents significant challenges for vocational high schools in preparing graduates who possess not only conceptual understanding but also practical skills in designing, programming, testing, and implementing IoT systems that meet industrial requirements and the growing adoption of IoT applications in areas such as industrial automation, smart agriculture, and smart healthcare (Asif et al., 2022; Chakraborty et al., 2023). Therefore, IoT instruction in vocational education should be designed through project-based activities, laboratory practice, and digital learning environments that progressively integrate hardware, software, data communication, and cloud services (Sulisworo et al., 2022; Amador Nelke et al., 2024; Kim, 2024; Tsipianitis et al., 2025). This approach is consistent with the principles of Project-Based Learning (PjBL),



which support the development of technical competencies and problem-solving skills through collaborative, project-oriented learning experiences (Guo et al., 2020).

However, implementing effective IoT instruction in vocational high schools remains challenging because IoT learning requires students to simultaneously develop competencies in programming, electronics, computer networks, sensors, actuators, data communication, and cloud services. Such multidisciplinary complexity requires students not only to understand programming logic but also to relate software development to electronic circuits and the practical implementation of IoT devices. Furthermore, introducing students directly to text-based programming often presents significant learning difficulties, particularly for beginners who must simultaneously comprehend programming syntax and logical thinking. Consequently, the learning process becomes increasingly complex and requires instructional approaches that provide appropriate scaffolding to facilitate gradual knowledge construction before students engage with real-world IoT implementation (Armesto et al., 2023). Such a progressive learning approach is also considered essential for bridging the transition from visual programming to text-based programming in IoT application development (Tselegkaridis et al., 2024).

Several studies have proposed instructional approaches to address these challenges. Lamprecht et al. (2021) demonstrated that block-based programming helps learners understand programming concepts through visual representations. Similar findings by Tan et al. (2022), and Armesto et al. (2023) showed that visual programming improves programming logic and reduces the complexity of text-based programming for novice learners. In parallel, web-based virtual laboratories have been shown to enhance laboratory flexibility, support debugging, and reduce the risk of hardware damage before implementation on physical devices (Atanasković et al., 2024; Wahyudi et al., 2025). Research on the Wokwi simulator further indicates that virtual simulation enables repeated experimentation and improves conceptual understanding in STEM and IoT learning (Munthakhabah et al., 2026; Yang et al., 2021). Furthermore, ESP32 has been widely recognized as a suitable platform for IoT education due to its support for wireless communication, sensor integration, and cloud-based applications (López & Lamo, 2023; Rofi'i et al., 2025). The integration of cloud platforms such as Blynk also enables real-time monitoring and control of IoT devices, making learning experiences more contextualized and closely aligned with industrial IoT applications (Sulisworo et al., 2022).

Although these studies have made significant contributions to Internet of Things (IoT) education, most have focused on a single instructional approach. Block-based programming has been shown to effectively improve students' understanding of programming logic through visual representations (Lamprecht et al., 2021; Tan et al., 2022; Tselegkaridis et al., 2024), but it is less suitable for developing more complex IoT systems. Virtual laboratories support circuit simulation, debugging, and program testing (Atanasković et al., 2024; Wahyudi et al., 2025; Munthakhabah et al., 2026; Yang et al., 2021), yet they do not provide authentic experience in implementing IoT devices. Meanwhile, the use of ESP32 and remote laboratories offers more authentic hands-on experience (Amador Nelke et al., 2024; Garefalakis et al., 2025), but it is often too complex for novice learners. Because of the limitations of each approach, an instructional approach that can address these weaknesses is needed. One possible solution is to integrate block-based programming, virtual laboratories, and real devices into a single instructional model, as these approaches have complementary characteristics that can compensate for each other's limitations.



Based on this gap, the present study develops an ESP32-based Internet of Things learning model integrating multiple instructional approaches through Project-Based Learning (PjBL). The proposed model integrates PictoBlox as a block-based programming platform, a C++ code conversion feature, the Wokwi virtual laboratory, Arduino IDE, ESP32, and the Blynk cloud platform into a systematic instructional framework. This integrated framework is designed to support students' learning through a scaffolding approach, beginning with programming logic development using block-based programming, followed by automatic conversion to C++, simulation and debugging in Wokwi, and finally the implementation of IoT systems on ESP32 devices connected to a cloud platform. Accordingly, the novelty of this study lies in the development of a project-based instructional model that systematically integrates these learning media and technologies into a single learning framework, an approach that has received limited attention in previous studies, particularly in the context of IoT education in vocational high schools.

Therefore, this study aims to develop an ESP32-based Internet of Things learning model integrating multiple instructional approaches through Project-Based Learning (PjBL) and to evaluate its feasibility and effectiveness in improving vocational high school students' learning outcomes in Internet of Things education. The study proposes a systematic instructional framework that integrates block-based programming, virtual laboratories, and real-device implementation* into a unified learning sequence to support progressive and integrated IoT learning.

Research Method

This study employed a Research and Development (R&D) approach to develop an ESP32-based Internet of Things (IoT) learning model integrating multiple instructional approaches through Project-Based Learning (PjBL). The model was developed using the ADDIE instructional design model and evaluated through a one-group pretest-posttest design. The study was conducted at SMK Kartika XIX-1 Bandung, Indonesia, from 14 April to 5 May 2026, involving 33 eleventh-grade vocational high school students selected through purposive sampling. The feasibility of the proposed model was evaluated by two expert validators, consisting of an educational technology lecturer and an IoT vocational teacher.

The research began with a literature review and needs analysis, followed by the development and expert validation of the instructional model, learning materials, and research instruments. The implementation phase consisted of a pretest, learning activities using the proposed model through block-based programming, virtual laboratory simulation, and real-device implementation, and a posttest to evaluate learning effectiveness. The overall research procedure is illustrated in Figure 1.

Research data were collected through classroom observation, expert validation, achievement tests, questionnaires, and documentation. Classroom observation was used to evaluate the implementation of the learning process, expert validation to assess the feasibility of the proposed instructional model, achievement tests to measure students' learning outcomes, and questionnaires to evaluate students' learning satisfaction. Prior to implementation, all research instruments underwent expert validation. The achievement test initially consisted of 40 multiple-choice items, of which 30 valid items were retained. The instrument demonstrated very high reliability ($KR-21 = 0.90$), with most items classified as having easy to moderate difficulty and good to very good discrimination indices.

The data were analyzed using descriptive and inferential statistics. Descriptive analysis summarized the results of expert validation, classroom observation, and

questionnaires. Inferential analysis included the Shapiro–Wilk normality test, followed by the Wilcoxon Signed-Rank Test because the data were not normally distributed. The effectiveness of the proposed instructional model was evaluated using Normalized Gain (N-Gain) based on Hake (1998), with gain scores classified as high ($g \geq 0.70$), medium ($0.30 \leq g < 0.70$), and low ($g < 0.30$).



Figure 1. Research Procedure

Results and Discussion

The initial stage of the study involved a needs analysis to identify challenges in Internet of Things (IoT) learning at the vocational high school level. The analysis was conducted through classroom observations, interviews with the subject teacher, and questionnaires administered to students. The results of the student questionnaire are presented in Figure 2.



Figure 2. IoT Learning Difficulties Analysis Results

As shown in Figure 2, programming was identified as the primary challenge in IoT learning, with 67.7% of students reporting difficulties. Additional challenges included understanding electronic circuits and IoT concepts (35.5% each), debugging (32.3%), understanding programming logic (54.8%), and identifying Arduino pin functions (48.4%). Classroom observations indicated that limited practical hardware reduced opportunities for independent hands-on activities, while teacher interviews revealed that students struggled to connect programming concepts with IoT implementation on physical devices.

These findings suggest that IoT learning requires a progressive integration of programming logic, simulation, and hardware implementation. Accordingly, this study developed an ESP32-based IoT learning model integrating multiple instructional approaches through Project-Based Learning (PjBL), combining PictoBlox for block-based programming, Wokwi as a virtual laboratory, and Arduino IDE, ESP32, and Blynk for real-device implementation.

Based on the results of the needs analysis, an ESP32-based Internet of Things (IoT) learning model was developed by integrating block-based programming, a virtual laboratory, and real-device implementation within a Project-Based Learning (PjBL) framework. The model was designed to address the main challenges identified during the needs analysis, namely students' difficulties in understanding programming logic, interpreting electronic circuits, and connecting theoretical concepts with their implementation on physical IoT devices. The development resulted in an instructional framework that illustrates a progressive learning pathway, guiding students from project planning to project evaluation through a sequence of structured learning activities. The proposed instructional framework is presented in Figure 3.

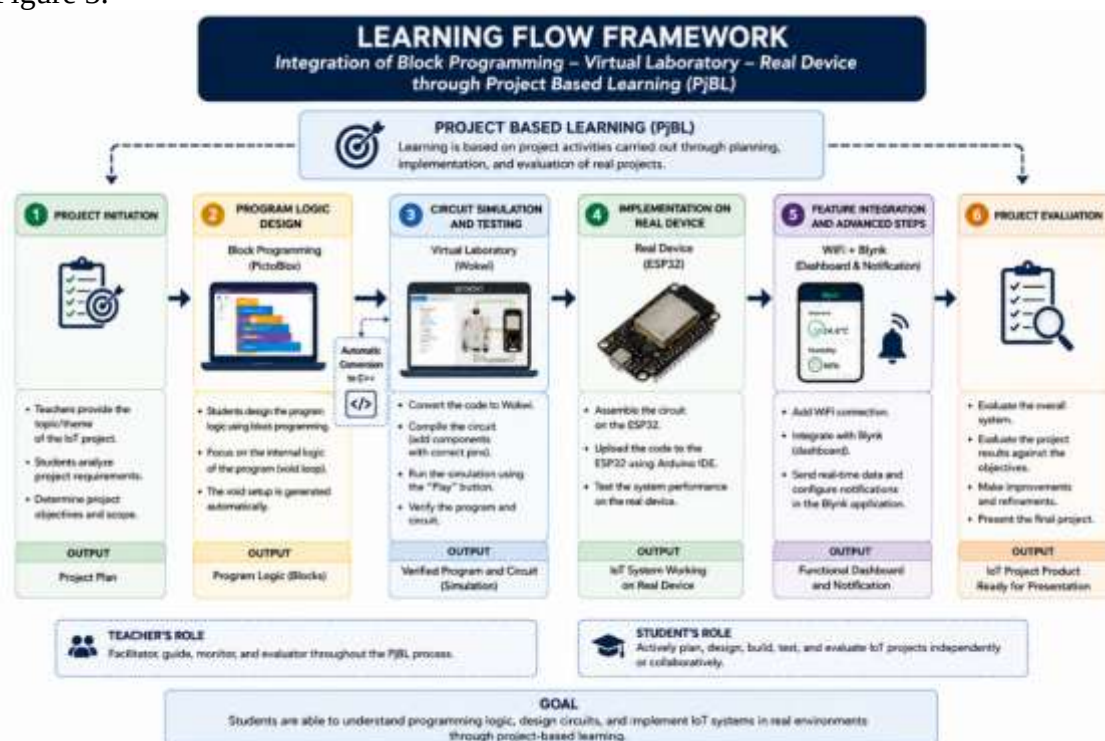


Figure 3. Learning Flow Framework

As shown in Figure 3, the proposed instructional framework consists of six interconnected learning stages that form a progressive learning sequence. The first stage is Project Planning, where the teacher introduces an IoT-related problem and students analyze project requirements, define learning objectives, and determine the project scope. The second stage is Block-Based Programming using PictoBlox, in which students develop programming logic through visual programming blocks that are automatically converted into C++ code to facilitate the transition to text-based programming. The third stage is Virtual Laboratory Simulation using Wokwi, where students simulate ESP32 circuits, test program functionality, and perform debugging before deployment on physical hardware. The fourth stage is Real-Device Implementation, during which the verified program is uploaded to an ESP32 board,



allowing students to gain hands-on experience with hardware integration and IoT system testing. The fifth stage is Advanced Feature Integration, which incorporates Wi-Fi connectivity and the Blynk platform to enable real-time monitoring and Internet-based device control. Finally, Project Evaluation involves testing the overall system, correcting identified issues, presenting the completed project, and reflecting on the learning process. Through these sequential stages, the framework supports the progressive development of students' competencies from programming logic and circuit simulation to real-device implementation and cloud-based IoT applications.

The proposed instructional framework demonstrates a clear relationship among all learning stages, in which the output of each stage serves as the input for the next. It also clearly defines the roles of both teachers and students throughout the learning process. Teachers act as facilitators, mentors, and evaluators, while students actively participate in planning, developing, testing, and evaluating IoT projects collaboratively. Consequently, the learning process emphasizes not only the completion of the final product but also the progressive development of students' understanding, beginning with programming logic construction, continuing through circuit simulation and real-device implementation, and culminating in the development of Internet-connected IoT systems.

The developed instructional model was subsequently implemented with 33 eleventh-grade students from the Teknik Komputer dan Jaringan (TKJ) program at SMK Kartika XIX-1 Bandung, Indonesia. Prior to classroom implementation, the proposed model underwent expert validation conducted by an educational expert and an IoT education practitioner. The expert validation results are presented in Table 1. As shown in the table, both validators rated 18 indicators as appropriate (S) and 1 indicator as partially appropriate (KS), resulting in a feasibility score of 94.7%. The average feasibility score was also 94.7%, which falls within the highly feasible category. These results indicate that the proposed instructional model met the required feasibility criteria and was suitable for implementation in the learning process.

Tabel 1. Expert Validation Results

Validator	Appropriate (S)	Partially appropriate (KS)	Feasibility score	Category
Educational expert	18	1	94.7	Highly feasible
IoT education practitioner	18	1	94.7	Highly feasible
Average	18	1	94.7	Highly feasible



Figure 4. Implementation of the IoT Learning Model



The learning activities were conducted in accordance with the proposed instructional framework through the implementation of Project-Based Learning (PjBL). Documentation of the learning implementation is presented in Figure 4. During the first stage (Figure 4a), students developed program logic using PictoBlox through a block-based programming approach, enabling them to construct the program flow visually. Subsequently, as shown in Figure 4b, students simulated electronic circuits and tested their programs using Wokwi as a virtual laboratory to verify both the circuit design and program functionality before deployment on physical hardware. The next stage (Figure 4c) illustrates the implementation of the verified program on an ESP32 development board, followed by testing of the assembled hardware system. After the system operated successfully, students integrated it with the Blynk platform to enable Internet-based monitoring and device control. The final implementation results are presented in Figure 4d, showing the dashboard interface and real-time notifications displayed in the Blynk application, indicating that the IoT system functioned as intended.

Following the completion of the learning implementation, an evaluation was conducted to determine the effectiveness of the proposed instructional model in improving students' learning outcomes. Learning effectiveness was assessed by comparing students' pretest and posttest scores, which were subsequently analyzed using the Wilcoxon Signed-Rank Test and Normalized Gain (N-Gain) analysis. In addition, students' perceptions of the instructional model were collected through a questionnaire to evaluate their level of acceptance and satisfaction with the proposed learning approach. The evaluation results are presented in the following section.

The effectiveness of the proposed instructional model was further examined based on students' learning outcomes, which were measured through a pretest administered before the learning activities and a posttest administered after the completion of the instructional intervention. The comparison of the mean pretest and posttest scores is presented in Figure 5. As shown in Figure 5, the students' mean pretest score was 70.00, while the mean posttest score increased to 90.10. These results indicate a substantial improvement in students' learning outcomes following the implementation of the proposed ESP32-based Internet of Things (IoT) learning model integrating multiple instructional approaches through Project-Based Learning (PjBL).

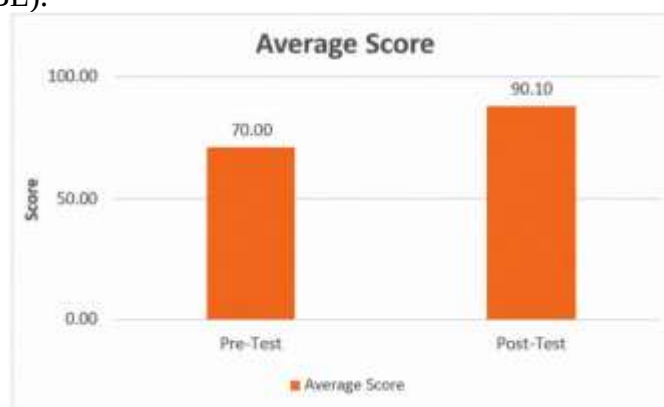


Figure 5. Pretest and Posttest Results

To determine whether the improvement in learning outcomes was statistically significant, a Wilcoxon Signed-Rank Test was performed. The analysis yielded an Asymp. Sig. (2-tailed) value of < 0.001 , indicating a statistically significant difference between



students' pretest and posttest scores. These findings demonstrate that the proposed instructional model had a significant positive effect on students' learning outcomes.

The effectiveness of the proposed instructional model was further evaluated using Normalized Gain (N-Gain) analysis based on students' initial ability levels. The results are presented in Figure 6. As shown in the table, students in the low initial ability group achieved the highest N-Gain score (0.77), which falls within the high category. Students in the medium initial ability group obtained an N-Gain score of 0.58, corresponding to the moderate category, whereas those in the high initial ability group achieved an N-Gain score of 0.15, which is classified as low. Overall, the average N-Gain score was 0.44, indicating a moderate improvement in learning outcomes.

Group	Description	Pre-Test Score	Post-Test Score	Gain	Gain Criteria
High	Maximum Score	97	100	0.15	Low
	Minimum Score	83	90		
	Average Score	96.19	95.93		
Medium	Maximum Score	93	100	0.58	Medium
	Minimum Score	53	53		
	Average Score	51.67	39.93		
Low	Maximum Score	50	100	0.77	High
	Minimum Score	13	40		
	Average Score	33.04	35.56		
Overall Average		60.30	57.14	0.44	

Figure 6. Comparison of N-Gain Scores Across Initial Ability Groups

These findings indicate that the proposed instructional model produced greater learning gains among students with low initial ability than among those with medium or high initial ability. This finding can be explained by Scaffolding Theory, which is grounded in Vygotsky's Zone of Proximal Development (ZPD), where learning support is provided progressively according to students' levels of understanding (Vygotsky, 1978). The learning sequence beginning with block-based programming, followed by virtual laboratory simulation using Wokwi, and culminating in real-device implementation using ESP32 enabled students to construct their understanding step by step before dealing with the complexity of physical IoT systems. This progressive learning process was particularly beneficial for students who initially experienced difficulties in programming logic and IoT system implementation. In contrast, the relatively smaller improvement observed among students with high initial ability may be attributed to their stronger prior knowledge before the intervention, leaving less room for measurable improvement in learning outcomes.

In addition to improving students' learning outcomes, the proposed instructional model also received positive responses from the participants. A total of 63.6% of the students reported that the learning activities helped them better understand Internet of Things (IoT) concepts. Furthermore, 81.9% of the students stated that PictoBlox facilitated their understanding of fundamental programming concepts, while 78.8% indicated that circuit simulation using Wokwi enhanced their understanding of electronic circuits before implementing them on physical hardware. Moreover, 84.8% of the students agreed that the integration of PictoBlox and Wokwi helped them better understand programming using the Arduino IDE. These findings indicate that the proposed instructional model was not only effective in improving students' learning outcomes but also well accepted by students,



supporting a more systematic and progressive approach to learning Internet of Things concepts.

Discussion

The effectiveness of the proposed instructional model can be attributed to the contribution of each component integrated into the developed instructional framework. The use of PictoBlox for block-based programming as the initial learning stage enabled students to understand programming logic before transitioning to text-based programming. This progressive instructional approach is consistent with the studies of Kim (2024) and Tsipianitis et al. (2025) which emphasize the importance of integrating sequential learning stages, hands-on activities, and technology implementation in Internet of Things (IoT) education. The findings are also consistent with those reported by Lamprecht et al. (2021) and Tan et al. (2022), who demonstrated that block-based programming facilitates students' understanding of programming concepts through visual representations. However, unlike previous studies, the proposed instructional model not only utilizes block-based programming as an introductory learning tool but also integrates an automatic conversion process to C++, enabling students to understand the relationship between visual programming and text-based programming before using the Arduino IDE. Furthermore, the integration of Wokwi as a virtual laboratory supports the findings of Atanasković et al. (2024) and Wahyudi et al. (2025), who reported that virtual simulation improves students' understanding while reducing errors during physical implementation. These findings are further supported by Garefalakis et al. (2025), who demonstrated that remote laboratories provide learners with greater flexibility to test IoT systems before deployment on physical hardware. In the proposed instructional model, Wokwi serves not only as a simulation platform but also as an environment for debugging and program verification before deployment on the ESP32, thereby making the learning process more effective and efficient.

The implementation of Project-Based Learning (PjBL) through smart security alarm and smart farming projects also provided students with authentic and contextual learning experiences by actively engaging them in the design, testing, and implementation of IoT systems. These findings support the work of Tsybulsky and Sinai (2022), who reported that Project-Based Learning enhances student engagement, problem-solving skills, and meaningful learning experiences. Similar findings were reported by Villanueva and Peppler (2023), who emphasized that authentic learning experiences through IoT project development strengthen students' engagement while bridging the gap between theoretical concepts and technological implementation. The present study also found that the greatest improvement in learning outcomes was achieved by students with low initial ability. This finding suggests that the systematic and progressive learning sequence effectively supported students in constructing their understanding step by step, thereby reducing the learning gap among students with different initial ability levels. Moreover, the integration of ESP32 and Blynk enabled students to experience real-time IoT implementation, supporting the findings of Rofi'i et al. (2025), who reported that the use of real IoT devices enhances both conceptual understanding and practical skills. These results are further corroborated by Ibrahim and Kenwright (2022), Oise et al. (2025), and Guo et al. (2022), who demonstrated that integrating IoT devices into learning environments creates more contextual, interactive, and authentic learning experiences.

Compared with previous studies, the primary contribution of this research lies in the development of an instructional framework that systematically integrates PictoBlox, Wokwi,



Arduino IDE, ESP32, and Blynk into a single Project-Based Learning workflow. This integration provides a coherent instructional sequence that guides students from programming logic construction and virtual simulation to real-device implementation and complete IoT project development, offering an alternative instructional model for IoT education in vocational high schools. Nevertheless, this study has several limitations. First, the implementation of the instructional model requires relatively longer instructional time because each learning stage must be completed sequentially. Second, the model remains dependent on the available features and supported components of the PictoBlox and Wokwi platforms. Finally, the proposed model was evaluated using only two IoT projects, namely a smart security alarm and a smart farming system; therefore, its applicability to other IoT application domains has not yet been comprehensively investigated. Future studies are recommended to evaluate the proposed instructional model across a wider variety of IoT projects, involve larger numbers of vocational schools, and examine its impact on twenty-first-century competencies, including critical thinking, creativity, collaboration, communication, and problem-solving skills.

Conclusion

This study successfully developed an ESP32-based Internet of Things (IoT) instructional model integrating multiple instructional approaches through Project-Based Learning (PjBL). The proposed model systematically integrates PictoBlox, Wokwi, Arduino IDE, ESP32, and Blynk into a unified instructional framework developed based on a comprehensive needs analysis and validated by experts prior to classroom implementation. The implementation results demonstrate that the proposed instructional model is both feasible and effective in improving students' learning outcomes. The integration of block-based programming, virtual laboratory simulation, and real-device implementation supports a progressive learning process that enables students to develop programming logic, understand circuit simulation, and implement IoT systems on physical devices. Furthermore, the model received positive responses from students, indicating that the proposed instructional approach provides a more meaningful, engaging, and systematic learning experience for IoT education in vocational high schools.

Recommendation

Based on the findings of this study, several recommendations can be proposed for vocational teachers, curriculum developers, and future researchers. For vocational teachers, the proposed instructional model is recommended as an alternative project-based IoT learning approach that progressively integrates block-based programming, virtual laboratory simulation, and real-device implementation. For curriculum developers, the model may serve as a reference for designing a more systematic and progressive IoT curriculum that supports the development of vocational competencies. For future researchers, the model should be evaluated across a wider range of IoT topics, vocational fields such as electronics and electrical engineering, and more diverse schools and student populations to provide broader evidence of its effectiveness.

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