IJORER : International Journal of Recent Educational Research
Homepage : https://journal.ia-education.com/index.php/ijorer
Email : ijorer@ia-education.com

p-ISSN : 2721-852X ; e-ISSN : 2721-7965
IJORER, Vol. 7, No. 1, January 2026
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The Utilization of the Wokwi Simulator Platform as a STEM Learning Innovation in the Internet of Things (IoT) Course

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DOI : https://doi.org/10.46245/ijorer.v7i1.1268

Sections Info

Article history:
Submitted: December 09, 2025
Final Revised: January 29, 2026
Accepted: January 30, 2026
Published: January 31, 2023

Keywords:
Internet of Things; Simulator Wokwi; Pembelajaran STEM

ABSTRAK

The purpose of this study is to examine the use of the Wokwi Simulator Platform as a STEM-based learning innovation in Internet of Things (IoT) courses in higher education. This study uses a qualitative approach with a single instrumental case study design involving 24 undergraduate students from one IoT practicum class at the Information Technology Education Study Program, University of West Sulawesi, in the period September–October 2025. Data were collected through semi-structured interviews, participatory observations, and learning documentation, and then analysed using the interactive analysis model Miles, Huberman, and Saldaña. The results revealed three main interrelated themes. First, the efficiency and flexibility of using Wokwi allows students to conduct repeated experiments without hardware limitations, thus encouraging the formation of active experimentation. Second, the virtual debugging process directs students to focus more on programming logic and scientific reasoning, thus strengthening the reflective observation stage. Third, holistic STEM integration is reflected through the use of real-time data visualisation features that help students understand the interconnectedness of cross-disciplinary concepts in the abstract conceptualisation stage. In the context of previous research on virtual labs and STEM-based IoT learning, these findings expand existing studies by presenting qualitative empirical evidence on how simulated environments support experiential learning processes rather than simply improving learning outcomes. This study concludes that the Wokwi Simulator Platform functions as an effective pedagogical medium in supporting STEM-oriented IoT learning, especially in the context of higher education with limited laboratory resources. These findings provide implications for designing IoT curricula that emphasise data-driven analysis and interdisciplinary integration, and further research is needed to examine the transfer of learning from virtual simulations to physical hardware implementations.

INTRODUCTION

The rapid development of digital technology in the era of the Fourth Industrial Revolution has placed the Internet of Things (IoT) as a strategic component of engineering and information technology education (Fonna, 2019). In the context of higher education, IoT courses not only play a role in equipping students with programming skills but also in developing the ability to integrate knowledge across Science, Technology, Engineering, and Mathematics (STEM) disciplines to support system design and technology-based problem-solving (Baghiroh et al., 2025).

Various previous studies (Thayban et al., 2025); (Todorova et al., 2025); (Nikitina & Ishchenko, 2023) have reported that IoT learning designed with a STEM approach makes a positive contribution to the development of students' cognitive, collaborative, and problem-solving abilities. However, the implementation of IoT practicums in universities still faces a number of structural obstacles, especially related to the high cost of hardware procurement, risk of component damage, and limited access to physical laboratories (Widarti et al., 2025). This often limits students' opportunities to conduct experiments repeatedly, even though experimental activities are an essential element in the formation of scientific reasoning and engineering design competencies.

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In an effort to overcome these limitations, virtual laboratories and simulation platforms are increasingly being used in engineering education (Frady, 2023). Platforms such as Tinkercad and Wokwi allow students to carry out programming and circuit design activities in a virtual environment so that the experimental process can be carried out without dependence on physical hardware (Bento et al., 2023). Among the various simulation platforms available, Wokwi has received special attention for its ability to simulate microcontrollers such as Arduino and ESP32 in real time, as well as being equipped with debugging and data visualisation features that support the learning process (Elakkiya et al., 2024).

However, studies related to the use of Wokwi and similar simulators are still dominated by quantitative approaches that focus on learning outcomes, such as improving grades, programming performance, or mastery of technical skills (Huizen & Hendrawan, 2025); (Candra et al., 2024); (Asparuhova et al., 2024). Although these findings demonstrate the effectiveness of simulation-based learning, the study does not fully explain how students cognitively and experientially interact with virtual simulation environments. In particular, understanding of how simulation supports the process of scientific reasoning, learning reflection, and cross-disciplinary integration of STEM is still relatively limited.

These limitations show that there is a research gap related to an in-depth qualitative understanding of the role of the simulation environment in shaping student learning experiences during the IoT practicum. In fact, understanding the learning process is important to ensure that the use of simulation technology is not only instrumental but also has meaningful pedagogical value.

Based on this background, this study aims to explore the use of the Wokwi Simulator Platform as a STEM-based learning innovation in Internet of Things (IoT) courses through a qualitative case study approach. This research focuses on the experiences of students and lecturers in examining how Wokwi supports the process of experimentation, reflection, and conceptual integration across STEM domains during learning activities.

In contrast to previous research that emphasised the effectiveness of outcome-based learning, this study contributes by placing simulation-based IoT learning within an experiential learning framework. Through a qualitative study of the learning process facilitated by Wokwi, this research is expected to expand the understanding of the role of virtual laboratories in engineering education. Practically, the findings of this study are expected to provide an empirical basis for the development of an IoT practicum curriculum that is adaptive, efficient in the use of resources, and able to support interdisciplinary STEM learning in higher education.

RESEARCH METHODS

This study used a qualitative approach with a single instrumental case study design to gain an in-depth understanding of the use of the Wokwi simulator platform in STEM-based Internet of Things (IoT) learning. The case in this study is defined as the implementation of Wokwi-based IoT practicum learning in an undergraduate IoT course in the Information Technology Education Study Program. The research analysis unit includes student learning experiences and lecturers' learning practices during the implementation of the IoT practicum, supported by the use of Wokwi simulators. Case limits were explicitly set in one IoT practicum class held at the University of West

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Sulawesi during an academic implementation period, namely from September to October 2025. These restrictions are intended to allow for a focused and contextual analysis of the learning process in real-world classroom situations.

Figure 1. Research Subjects of Information Technology Education Students

The case study approach was chosen because it allows for a comprehensive exploration of contemporary educational phenomena, particularly virtual laboratory learning, in the context of in-person learning (Hassan et al., 2022). Through this design, the research aims to produce an in-depth description of how the Wokwi Simulator Platform supports STEM integration, experimental activities, and the formation of students' conceptual understanding. In addition, this approach is expected to provide an empirical foundation for the development of a simulation-based IoT practicum curriculum and the formulation of virtual laboratory guidelines in higher education. This research was carried out in five systematic stages:

1. The first stage, namely the preparation stage, includes determining the focus of the research, preparing semi-structured interview instruments, and planning learning observations. The research instruments and guidelines were validated by two educational technology experts to ensure methodological accuracy and scientific reliability. The first expert is a senior lecturer in the field of Educational Technology with more than 15 years of experience in digital learning design and learning media development. The second expert is a Computer Engineering lecturer who has expertise in the development of IoT learning media and the implementation of virtual laboratories. Input from both experts was used to refine the interview guidelines, observation guidelines, and documentation procedures.
2. The second stage, the stage of selecting research subjects, was carried out using purposive sampling techniques. The research informants consisted of 24 undergraduate program students in 2024 who were enrolled in one IoT practicum class and actively used the Wokwi simulator during learning activities. In addition to students, one lecturer teaching the IoT course was also involved as an informant to provide a learning perspective from the instructional side. The selection of informants was carried out until data saturation was achieved, which was characterised by the emergence of repeated answer patterns and the absence of new themes from the results of interviews and observations.
3. The third stage, namely the data collection stage, is carried out simultaneously through three main techniques: semi-structured interviews, participatory observations, and learning documentation. The use of these techniques aims to enrich the data and increase the validity of the findings through the triangulation of methods.

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4. The third stage, namely the data collection stage, is carried out simultaneously through three main techniques: semi-structured interviews, participatory observations, and learning documentation. The use of these techniques aims to enrich the data and increase the validity of the findings through the triangulation of methods.
5. The fifth stage, namely, the reporting stage, is carried out by compiling research findings in the form of a structured thematic narrative and an analysis matrix. The findings are then interpreted by linking them to STEM learning theory and experiential learning frameworks, and end with the formulation of implications and recommendations for the development of a simulation-based IoT practicum curriculum.

Data collection in this study applies methodological triangulation using three main techniques (Susanto & Jailani, 2023):

1. **Semi-Structured Interviews**
   The interviews were conducted to explore the perceptions, learning experiences, and challenges faced by students and lecturers in using the Wokwi Simulator during learning. The interview questions were structured based on indicators of STEM integration, scientific reasoning, and programming practices.
2. **Participatory Observation**
   The researcher conducted direct observations of the implementation of IoT practicum sessions to document learning activities, interactions between students, collaboration patterns, and problem-solving strategies that emerged in the virtual simulation environment.
3. **Documentation**
   Digital documents and artefacts, such as Wokwi project files, simulation logs, student assignments, and interview transcripts, were collected as supporting data sources to strengthen the data triangulation process.

Primary data are obtained directly from students and lecturers, while secondary data include course syllabus documents and guidelines for practicum implementation. Data analysis was carried out using the Miles, Huberman, and Saldaña Interactive Analysis Model which includes the stages of data reduction, data presentation, and conclusion drawing with a verification process that takes place on an ongoing basis (Salmona and Kaczynski, 2024). At the data reduction stage, interview transcripts, observation notes, and learning documents were analysed through a systematic coding process to identify repetitive patterns related to the frequency of experiments, duration of simulator use, changes in learning behaviour, and the STEM integration process. Descriptive indicators, such as the number of simulation experiments conducted, length of student involvement in the practicum, and pattern of interaction during learning, were extracted to strengthen the empirical foundation of the research findings.

In the data presentation stage, the data that have been reduced are arranged in the form of a thematic matrix and a descriptive-analytical narrative. Interview excerpts are presented as empirical evidence, while tables and images—in the form of simulation screenshots and learning activities—are analytically linked to specific themes to illustrate observed learning behaviours rather than simply as visual complements.

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Conclusions were drawn through an iterative interpretation and verification process by applying a continuous comparison between data sources and member checking to a number of selected participants. Source triangulation was carried out by comparing data obtained from students and teaching lecturers, while triangulation methods were used to ensure consistency in the findings between interviews, observations, and documentation. This series of analytical procedures aims to improve the credibility, dependability, and validity of research findings, as well as ensure that there is a clear distinction between empirical data and researcher interpretation.

RESULTS AND DISCUSSION

Result

This research identifies three main themes that represent the experience of students and lecturers in utilising the Wokwi Simulator Platform as a STEM-based learning innovation. These themes were obtained through a systematic thematic analysis of semi-structured interview data (n = 24 students; two lecturers), participatory observations in class conducted during six practicum sessions, and digital learning artefacts that included simulation logs, source code, and practicum reports.

Efficiency and Flexibility as Drivers of Active Experimentation.

Empirical evidence obtained from observational records and documentation logs showed a significant increase in the intensity of student experiments after the implementation of Wokwi. Observational data showed that students conducted an average of four to six simulations in each practicum session, compared to one to two experiments when using physical hardware. In addition, the platform's access logs show that 18 out of 24 students are actively conducting self-simulations outside of scheduled lecture hours, with an average usage duration of 45–70 minutes per session.

The interview data corroborated the findings by showing that the use of Wokwi reduced students' anxiety levels related to the risk of hardware damage and component cost limitations. Students explicitly attributed this condition to increasing their courage to explore alternative codes and network configurations. One of the students stated:
"When using hardware, I am afraid of misconnecting the cables because it can damage the components and cost money. With Wokwi, I could repeat the experiment five times in an hour without worry. This makes me more confident to explore." (Interview, Subject A).

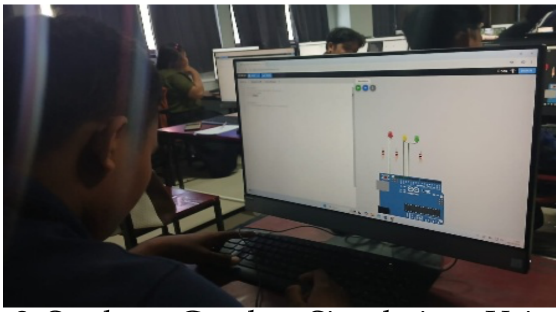

Figure 2. Students Conduct Simulations Using Wokwi

Figure 2 illustrates a typical simulation session in which students repeatedly modify the parameters of the code and components of the circuit. Analytically, this visual evidence confirms the shift in learning behaviour from careful execution to

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iterative experimentation, which indicates the emergence of the active experimentation phase, as described in experiential learning theory.

Deep Reflection through Virtual Debugging Cycle (Reflective Observation)

Interview data and observation notes show that the debugging environment in Wokwi encourages the reflective learning process by minimising physical disturbances. During the observed practicum sessions, students allocated an average of approximately 60% of the learning time to analyse error messages, Serial Monitor outputs, and program logic structures. This percentage is much higher than that of hardware-based practicums, where about 30% of students' time is spent on wiring and component troubleshooting. Students interpreted simulation failures as a moment of analytical reflection and not as a source of technical frustration. This is reflected in the following statement:

> "*When the simulation failed, I immediately checked the Serial Monitor and the flow of the program's logic. It forced me to think scientifically, not just fix the cables.*" (Interview, Subject B).

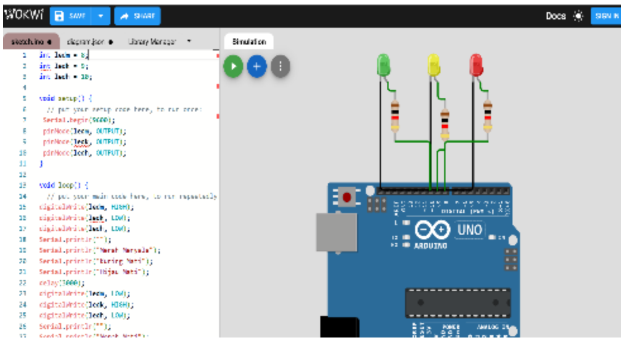

Figure 3. Wokwi Simulator Display During the Simulation Process

Figure 3 shows the Wokwi simulation interface during the debugging process. This visual representation is analytically related to the students' reflective process, as it shows a real-time feedback mechanism that directs students to focus on the cause-and-effect relationship between code logic and system behaviour. These findings indicate that Wokwi supports the reflective observation phase by positioning students as conceptual problem-solvers, not just hardware operators.

Holistic STEM Integration through Design and Analysis (Abstract Conceptualization)

Evidence of the occurrence of the abstract conceptualisation phase can be seen in the students' ability to integrate schematic design, programming logic, and data interpretation. Analysis of the practicum report document showed that 21 out of 24 students explicitly referred to the graphical data output of the Serial Plotter feature in explaining the behaviour of the IoT system they designed. Students consistently attribute changes to sensor graphics to modifications to code structures, reflecting the integration of engineering logic, as well as mathematical and scientific reasoning.

This finding was reinforced by the results of the interview, as expressed by one of the students:' The Plotter feature really shows the mathematical aspect. When I changed the code, the graphics changed instantly. It helps me understand concepts, not just syntax." (Interview, Subject C).

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The visual artefacts generated through the Serial Plotter not only serve as illustrations but also as analytical tools that allow students to abstract general principles from experimental data. This shows the formation of mature STEM integration, where the aspects of Science, Technology, Engineering, and Mathematics converge in one simulation-based learning ecosystem.

Discussion

This study provides empirical guidance for lecturers and higher education institutions regarding the pedagogical placement of simulation-based learning in IoT education. First, the research findings confirm that Wokwi should not be viewed solely as a substitute for a physical laboratory but rather as a strategic pedagogical tool that supports the development of cognitive problem-solving skills, iterative experimentation, and data-driven analytical thinking skills (Nikitina and Ishchenko, 2023). The increase in the frequency and duration of student experiments shows that the simulation environment can reduce psychological and logistical barriers in learning (Yusiani et al., 2025), thus encouraging deeper involvement in the engineering problem-solving process.

Second, the results of the study show that the STEM-based IoT curriculum needs to explicitly integrate simulation-based data analysis activities, such as the systematic exploration of Serial Plotter features, as a mandatory learning component. This integration strengthens the mathematical dimension in STEM through real-time visualisation and interpretation of sensor data, in line with previous findings on the importance of data literacy in engineering education (Syaputra et al., 2023). However, this study also revealed that the effectiveness of these features is highly dependent on the existence of structured instructional guidelines. Without clear scaffolding, some students tend to focus on the results of code execution rather than on the meaning of the underlying mathematical patterns.

Third, although the research findings support the development of efficient and resource-friendly simulation-based practicum modules in line with the STEM–IoT Learning Framework proposed by Abichandani et al. (2022) and Habib et al. (2021), this study also highlights the existence of contextual limitations. Simulation-based learning appears to be most effective in the early and intermediate stages of conceptual understanding, particularly for abstract reasoning and debugging logic (EVI 2024). In contrast, advanced competencies related to hardware handling, physical sensor calibration, and real-world system uncertainties require complementary physical laboratory experiences (Mardizal et al., 2024). Thus, simulations are more appropriately positioned as a medium of preparation and reinforcement of learning rather than as a full substitute for hardware practice.

From a theoretical perspective, this study enriches the application of Kolb's Experiential Learning Theory (ELT) in the context of digital learning environments. The findings show that Wokwi effectively supports the reflective observation and abstract conceptualisation phases by minimising physical distractions and allowing students to focus on conceptual reasoning as well as data interpretation (Asparuhova et al., 2024); (Bento et al., 2023). However, the active experimentation phase in a virtual environment has limitations in terms of the tactical and sensory experience aspects commonly found in physical laboratories, which are important for the formation of embodied

p-ISSN : 2721-852X ; e-ISSN : 2721-7965
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engineering skills. These limitations underscore the need for a hybrid pedagogical model that strategically combines virtual simulation and physical experimentation.

Overall, this discussion goes beyond the confirmatory approach by acknowledging the advantages and limitations of simulation-based IoT learning. By placing the research findings in the context of the existing literature and critically examining the conditions in which Wokwi is the most and least effective, this study provides a balanced conceptual synthesis for the development of STEM-oriented engineering education. Further research is suggested to examine the transfer of learning outcomes from virtual simulations to physical hardware implementation at different levels of expertise and institutional contexts.

CONCLUSION

This qualitative instrumental case study research explores in depth the use of the Wokwi Simulator Platform as a STEM-based learning innovation in Internet of Things (IoT) courses. The results show that Wokwi not only functions as a substitute for physical hardware but also as a pedagogical medium that meaningfully supports the Experiential Learning Theory (ELT) cycle proposed by Kolb in a virtual learning environment.

Three interrelated themes emerged from the thematic analysis. First, in the Active Experimentation phase, students engage in intensive self-exploration, facilitated by the loss of risks associated with the use of hardware. Empirically, learning logs and observation results show that most participants perform repetitive self-simulations outside of scheduled lecture hours, with some students reporting four to six experiment cycles in a single practicum session, an intensity rarely found in previous hardware-based practicums. Second, the Reflective Observation phase is strengthened when students focus on program logic and scientific reasoning through a virtual debugging process, so that the cognitive burden due to physical wiring and component failures can be minimised. Third, Holistic STEM Integration (Abstract Conceptualisation) is reflected in students' ability to relate schematic design, programming logic, and sensor data visualisation through the Serial Plotter feature, which allows them to conceptualise the relationship between Science, Technology, Engineering, and Mathematics in one integrated digital environment.

Based on these findings, this study concludes that Wokwi is an effective and efficient pedagogical support tool for STEM-oriented IoT learning, especially in institutions with limited laboratory resources. However, claims about "transformational" impacts need to be interpreted with caution, given that this research was conducted in an institutional context with a qualitative design. Therefore, the results of this study are more representative of the depth of the learning experience than the broad generalisations of various educational contexts.

Practical Implications. Instead of positioning Wokwi as a universal replacement for physical laboratories, this study recommends its strategic integration as a complementary learning medium. In particular, Wokwi is most effectively used to (1) support early stage conceptual understanding and debugging skill development, (2) increase the frequency of experiments through low-risk simulations, and (3) facilitate data-driven analysis by utilising visualisation tools such as serial plotters. Educational institutions are advised to integrate structured simulation tasks— for example, minimum iteration requirements or guided data interpretation activities—into IoT

p-ISSN : 2721-852X ; e-ISSN : 2721-7965
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practicum modules so that exploratory learning remains analytically directional and pedagogically measurable.

Limitations and Recommendations for Advanced Research. This study has limitations in the context of a single case study, a relatively short duration of implementation, and reliance on qualitative data based on self-reports and observations. Therefore, further research is recommended to (1) use a comparative quantitative design or mixed methods to measure the difference in learning outcomes between simulation-based practicum and physical hardware, (2) conduct longitudinal studies to examine skill transfer from virtual simulations to real hardware environments, and (3) replicate research across various courses and institutions to strengthen external validity.

Overall, this study shows that virtual lab simulations like Wokwi not only digitise existing learning practices but have the potential to reshape experimental learning towards more reflective, iterative, and data-oriented engineering educationwhen applied with appropriate pedagogical constraints and instructional design.

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p-ISSN : 2721-852X ; e-ISSN : 2721-7965
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