



DESIGN AND EVALUATION OF AN IMMERSIVE AUGMENTED REALITY–INTEGRATED VIRTUAL LABORATORY FOR PLC PNEUMATICS

Mukhlidi Muskhir*	Universitas Negeri Padang, Padang, Indonesia	muskhir@ft.unp.ac.id
Afdal Luthfi	Universitas Negeri Padang, Padang, Indonesia	afdalluthfi02@gmail.com
Hansi Effendi	Universitas Negeri Padang, Padang, Indonesia	hans_79@ft.unp.ac.id
Dedy Irfan	Universitas Negeri Padang, Padang, Indonesia	dedy_irf@ft.unp.ac.id
Roni Eka Rahmat	UIN Sjech M. Djamil Djambek Bukittinggi, Indonesia	roniekarahmat@gmail.com

* Corresponding author

ABSTRACT

Aim/Purpose	This study addresses the limitations of conventional PLC and pneumatics laboratory learning, including high equipment costs, safety risks, limited hands-on time, and low interactivity. The purpose of this research is to design and evaluate an Augmented Reality–Integrated Virtual Laboratory (ARViLab) to improve student learning outcomes in PLC-Pneumatics education.
Background	Although Augmented Reality (AR) has been widely used in engineering education, most existing applications remain passive and lack deep integration with real-time PLC programming and interaction with pneumatic systems. This study addresses that gap by developing an immersive, interactive AR-based virtual laboratory that integrates PLC control logic and pneumatic actuators into a single learning ecosystem.
Methodology	This research employed a Research and Development (R&D) approach based on a modified Borg and Gall model. The study involved 60 undergraduate Electrical Engineering Education students, selected through proportional random

Accepting Editor Vishal Shah | Received: March 4, 2026 | Revised: June 15, August 23, 2026 |

Accepted: September 15, 2026.

Cite as: Muskhir, M., Luthfi, A., Effendi, H., Irfan, D., & Rahmat, R. E. (2026). Design and evaluation of an immersive augmented reality–integrated virtual laboratory for PLC pneumatics. *Journal of Information Technology Education: Innovations in Practice*, 25, Article 42. <https://doi.org/10.28945/5883>

(CC BY-NC 4.0) This article is licensed to you under a [Creative Commons Attribution-NonCommercial 4.0 International License](#). When you copy and redistribute this paper in full or in part, you need to provide proper attribution to it to ensure that others can later locate this work (and to ensure that others do not accuse you of plagiarism). You may (and we encourage you to) adapt, remix, transform, and build upon the material for any non-commercial purposes. This license does not permit you to use this material for commercial purposes.

	sampling, who were divided into experimental ($n = 30$) and control ($n = 30$) groups. Data were collected using expert validation questionnaires (analyzed with Aiken's V), practicality questionnaires (descriptive percentage), and learning outcome tests (N-Gain, paired-sample t -test, independent t -test, and ANCOVA) using IBM SPSS Statistics 26.
Contribution	This study contributes to the body of knowledge by proposing a comprehensive AR-integrated virtual laboratory framework that combines immersive simulation, PLC ladder programming, and pneumatic actuator interaction. It extends prior AR research by moving beyond passive visualization to an interactive, system-level learning environment supported by empirical testing of effectiveness.
Findings	The results indicate that ARViLab is valid (Aiken's V material = 0.85; media = 0.95) and very practical (85.61%). The experimental group achieved a medium N-Gain (0.65), significantly higher than the control group (0.29). Independent t -test results ($t = 10.32$, $p < 0.001$) and ANCOVA findings ($F = 107.355$, $p < 0.001$; $\eta^2 = 0.653$) demonstrate that ARViLab significantly improves student learning outcomes compared to conventional methods.
Recommendations for Practitioners	Educational institutions are encouraged to integrate AR-based virtual laboratories as preparatory simulation tools prior to physical practicum sessions to optimize equipment use, reduce operational risks, and enhance students' readiness and conceptual understanding.
Recommendations for Researchers	Future researchers should adopt mixed-method approaches to explore cognitive, affective, and behavioral impacts of immersive learning. Broader and more diverse samples across institutions are recommended to enhance generalizability.
Impact on Society	The implementation of ARViLab offers a scalable and cost-effective solution to improve technical workforce preparation in the era of Industry 4.0. By enhancing practical competencies in automation and control systems, this innovation supports the development of skilled graduates ready for modern industrial environments.
Future Research	Future studies should conduct longitudinal investigations to assess long-term skill retention and transferability to real industrial contexts. Further development may integrate Virtual Reality (VR), multi-user collaboration features, and Artificial Intelligence (AI)-based adaptive feedback systems to create intelligent immersive learning environments.
Keywords	augmented reality, virtual laboratory, PLC pneumatics, immersive learning, learning outcomes

INTRODUCTION

The Fourth Industrial Revolution has instigated profound changes in the global industrial sector, necessitating automation and intelligent control systems as essential components (Adel, 2024; Alia & El Harmouzi, 2024; George, 2024). One such transformation is the integration of Programmable Logic Controllers (PLCs) with pneumatic systems, an essential skill that electrical and industrial automation engineers must master. Mastery of practical skills in designing, implementing, and troubleshooting PLC-pneumatic systems is crucial to meet the need for a competent workforce capable of adapting to modern industrial technology (Lovrec, 2019; Triatmaja et al., 2024). Therefore, higher education and vocational institutions are responsible for providing learning experiences that integrate strong theoretical foundations with rich practical exposure (Gauthama et al., 2025; Kovalchuk et al., 2023).

However, conventional learning methods that rely on physical laboratories often face significant challenges. The main limitations include the high cost of investing in and maintaining equipment, the risk of component damage due to student errors, and occupational safety (Ali et al., 2024; Esen et al., 2025; Iswan, 2024; Margheritti et al., 2025; Rafa et al., 2024). In addition, accessibility constraints, such as a limited number of workbenches, are often disproportionate to the number of students, thereby reducing individual practice time (hands-on time) and learning effectiveness (Doerner & Horst, 2022; Volansky, 2020; K. Wang et al., 2025). Scalability to accommodate more complex and diverse industrial scenarios is also difficult to achieve in a static physical laboratory environment (Shamsuzzaman et al., 2024; Vilches et al., 2025).

In response to these challenges, innovations in educational technology, particularly immersive technology, offer a new paradigm in engineering education. Technologies that use Augmented Reality (AR) have shown great potential to revolutionize the delivery of practical and procedural materials (Aggarwal et al., 2024; Irfan et al., 2024; Rizvi et al., 2025). Suhail et al. (2024) found that implementing Augmented Reality (AR) in engineering education enhances student engagement and understanding of complex subjects. This technology creates a learning space that is interactive, safe, and easy to access. It also creates simulations that closely resemble real life without the need for expensive hardware. This means that problems that come with traditional labs can be solved in other ways.

The advancement of AR-based virtual laboratories enables students to participate in an immersive three-dimensional simulation environment (Criollo-C et al., 2021; Fortuna et al., 2024; Neffati et al., 2021; Shi et al., 2026). In virtual laboratory-based learning media, users can assemble pneumatic components, connect cables to PLC modules, upload programs, and test system functionality interactively. This virtual environment provides a safe platform for conducting repeated experiments, making mistakes without financial consequences or danger, and visualizing internal processes that are not visible on physical devices. The technique has proven effective in strengthening conceptual understanding and problem-solving skills.

Conversely, AR technology acts as a conduit between the digital and physical realms (Kiryakova, 2020; Romano et al., 2023). AR can present contextual information, such as assembly instructions, schematic diagrams, or real-time sensor data, virtually overlaid on real objects. In the context of PLC-Pneumatics learning, AR can be used to provide step-by-step guidance when students interact with physical equipment or to visualize the flow of compressed air inside valves and cylinders, thereby enriching their understanding of the working principles of components in depth.

Although previous research has examined the application of Augmented Reality (AR) to visualization in engineering education, significant research gaps remain. Most current AR applications are passive and only allow users to identify parts or view 3D models without interacting with the PLC device (Sukardjo et al., 2023; Widodo et al., 2024). The main gap is the lack of an AR platform that serves as an interactive virtual laboratory for integrated systems such as PLCs and Pneumatics. Therefore, this research aims to provide a comprehensive augmented reality learning ecosystem that enables students not only to observe but also to actively design, test, and improve control circuits virtually, facilitating a smooth transition from abstract principles to concrete applications.

This study seeks to develop and evaluate an Augmented Reality–Integrated Virtual Laboratory (ARViLab) for PLC-pneumatics education. The proposed learning environment is designed to improve the learning outcomes of electrical engineering students by providing risk-free experimentation in a virtual laboratory and guided interaction with real equipment through augmented reality. The study evaluates whether ARViLab is valid, practical, and effective for classroom implementation. This research specifically seeks to address the following inquiries:

1. How can an immersive AR-integrated virtual laboratory be designed and validated to support PLC-pneumatic learning?
2. To what extent is the proposed system practical and acceptable for students?

3. What is the effect of the system on students' learning outcomes compared to conventional learning?

The remainder of this article is organized as follows. The next section reviews relevant literature on augmented reality, virtual laboratories, simulation-based learning, and immersive technologies in engineering education, with particular attention to their potential and limitations in supporting practical skill development. The methodology section then explains the research and development design, participants, treatment procedures, data-collection instruments, and data-analysis techniques used to evaluate ARViLab. The results section presents the development process, expert validation, practicality testing, and empirical findings related to student learning outcomes. The discussion section interprets these findings in relation to prior studies, highlights ARViLab's contribution to PLC-pneumatics learning, and discusses practical implementation issues. Finally, the article summarizes the main findings, acknowledges the study's limitations, and outlines directions for future research.

LITERATURE REVIEW

The application of Augmented Reality (AR) in engineering education has advanced rapidly and has had a significant positive impact on the learning process. This development reflects the increasing need for learning environments that can connect theoretical knowledge with practical experience, particularly in technical fields such as electrical engineering, industrial automation, and control systems (Suhail et al., 2024; Šulc et al., 2023). As shown in Figure 1, a bibliometric review by Lampropoulos et al. (2025), which analyzed 235 publications from 2011 to 2025, indicates that this immersive technology plays an important role in increasing attention and focus on research on the use of AR in engineering education. Research shows that the use of AR in engineering education significantly improves students' conceptual understanding, laboratory competence, and motivation to learn compared with conventional techniques (Kulkarni & Harne, 2024; Liu et al., 2025; Mokmin et al., 2024; Singh et al., 2019; Suhail et al., 2024). AR technology has been shown to increase student motivation, creativity, and learning outcomes through interactive, contextual three-dimensional (3D) object visualization (Çeken & Taşkın, 2025). In addition, AR can create safe virtual and remote laboratories, allowing students to practice practical skills without risking damage to physical equipment. These characteristics make AR relevant for engineering education because students are required not only to observe technical concepts but also to understand procedures, system relationships, and equipment operation in a more concrete learning environment (Singh et al., 2019; Suhail et al., 2024).

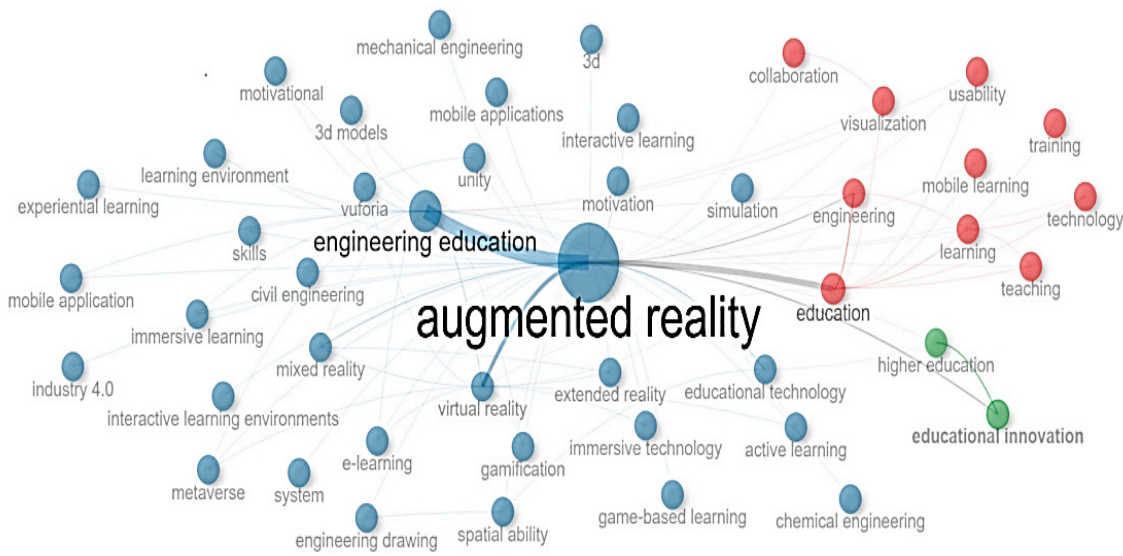


Figure 1. Visualization of keyword co-occurrence networks

In the context of modern engineering education, which requires integrating theoretical understanding with practical experience, AR is an innovative solution because it provides an interactive, immersive, and low-risk learning environment. Previous studies have shown that AR-based virtual laboratories are effective in facilitating independent and collaborative learning (Šulc et al., 2023), as well as in improving the quality of practical learning, reducing cognitive load, and decreasing student anxiety when operating laboratory equipment (Suhail et al., 2024). In addition to AR, Virtual Reality (VR) and immersive simulation environments have also been widely used to support laboratory-based learning. VR allows students to interact with fully simulated environments, while AR connects digital objects with real-world learning contexts. Both technologies support repeated practice, risk-free experimentation, and visualization of complex systems before students interact with real equipment (Doerner & Horst, 2022; Rafa et al., 2024; Sanzana et al., 2024). In addition, the use of AR can improve students' understanding of control system concepts through more intuitive and interactive visual representations. These benefits are even more important for learning pneumatic PLC, which requires spatial understanding, circuit visualization, and complex control logic (Habibi & Fieschko, 2020).

In pneumatic PLC learning, students must understand the relationships among ladder logic, electrical signals, pneumatic components, actuator movements, and troubleshooting procedures. Therefore, immersive and simulation-based learning can help students test procedures, identify errors, and refine their understanding before conducting direct practice in the physical laboratory (Habibi & Fieschko, 2020; Sanzana et al., 2024). Furthermore, AR technology can address various limitations of conventional practical learning, such as equipment constraints, high operational costs, safety risks, and limited practice time (Singh & Ahmad, 2024). These findings reinforce the urgency of research into the design and evaluation of immersive AR-integrated virtual laboratories for pneumatic PLC as a relevant and sustainable learning innovation.

Although various studies have shown significant benefits of AR in engineering education, a literature review also identifies several research gaps that remain to be addressed. Research by Álvarez-Marín and Velázquez-Iturbide (2022) emphasizes that many current educational AR applications remain limited in interactivity and therefore do not fully support active and exploratory learning. Many AR applications are still limited to object recognition, marker scanning, or passive visualization of 3D components. Such applications can support observation, but they do not always provide sufficient opportunities for students to manipulate systems, test control logic, or engage in problem-solving activities (Álvarez-Marín & Velázquez-Iturbide, 2022; Suhail et al., 2024). Previous studies have developed virtual laboratory-based electro-pneumatic learning media and reported improvements in media feasibility and students' procedural understanding (Sukardjo et al., 2023). However, these studies remained focused on pneumatic simulation without deep integration with real-time PLC programming or augmented reality. The focus remained limited to pneumatic simulations, with no deep integration with real-time PLC programming, and it did not use AR technology. This indicates that previous studies have provided important foundations for virtual and simulation-based pneumatic learning, but they have not fully integrated AR visualization, PLC programming, and pneumatic actuator interaction into a single immersive learning ecosystem (Sukardjo et al., 2023).

In addition, there are still shortcomings in the standardization of pedagogical frameworks and comprehensive evaluation methods, which are important to ensure the effectiveness of AR implementation in the context of technical learning (Suhail et al., 2024). The high visual complexity of some AR applications can also cause cognitive overload if not accompanied by adequate instructional scaffolding. Recent literature also emphasizes the necessity of a user-centered design approach in developing AR applications, as well as the importance of more in-depth empirical testing within specific technical domains to understand better the benefits, limitations, and pedagogical implications of this technology. Other practical challenges also need to be considered, including device compatibility, lecturer readiness, technical support, maintenance of digital content, and students' familiarity with immersive learning environments (Álvarez-Marín & Velázquez-Iturbide, 2022; Suhail et al., 2024).

These issues show that AR implementation should be evaluated not only from the perspective of technological novelty but also from its pedagogical relevance, usability, sustainability, and effectiveness in improving learning outcomes (Mokmin et al., 2024; Suhail et al., 2024).

Based on these gaps, this study aims to design and evaluate an immersive virtual laboratory integrated with AR (Augmented Reality), specifically focused on pneumatic PLC learning. This study uses AR to visualize components and integrates immersive interactions among PLC programming, control logic, and PLC actuators in a virtual environment. Unlike passive AR applications that mainly display 3D objects, ARViLab is designed as an interactive learning environment that enables students to observe components, assemble virtual circuits, design and test PLC ladder logic, and visualize the response of pneumatic actuators. This study enhances the technical dimensions by creating a realistic, interactive, 3D model-based virtual laboratory environment and employing a user-centered design methodology. This research also makes an empirical contribution by thoroughly assessing improvements in student learning outcomes. Therefore, the contribution of this study lies not only in developing an AR-based learning medium but also in proposing a system-level AR-integrated virtual laboratory that combines visualization, simulation, interaction, and empirical evaluation. Therefore, this research aims to address current knowledge gaps while providing a systematic framework for designing and evaluating immersive technologies in advanced control-system learning labs, especially for pneumatic PLC learning.

METHODOLOGY

RESEARCH METHODS AND PROCEDURES

This research employed a Research and Development (R&D) approach to design, develop, and evaluate an immersive learning product, a PLC-Pneumatics virtual laboratory integrated with Augmented Reality (AR). The development process adopted a modified Borg and Gall model (Wulansari et al., 2024), as shown in Figure 2. This model is deliberately designed to support rapid prototyping and the iterative nature of immersive technology development while maintaining methodological rigor. By focusing on essential stages such as needs analysis, expert validation, and user testing, this model facilitates an efficient yet systematic development cycle that is practical for the vocational education context.



Figure 2. Fishbone diagram

The study procedure was carried out through five sequential and interconnected stages, as shown in Figure 2. The analysis stage included needs analysis, analysis of the Semester Learning Plan, and literature review to identify gaps and requirements in PLC-Pneumatics practical learning. The subsequent stage was the development phase, which focuses on designing and creating an immersive virtual laboratory, encompassing system architecture, digital content production, UI/UX design, and virtual practice scenarios. The validation phase involved focus group discussions and expert evaluations to

assess content accuracy, technological feasibility, and instructional relevance. The findings informed subsequent product revisions. The subsequent stage of testing and implementation assessed the viability of the educational medium and its effect on student competencies. These steps yield learning media products that are valid, practical, and effective, enhancing student learning outcomes within the PLC Pneumatics framework.

PARTICIPANTS

The participants in this study were undergraduate students involved in the Electrical Engineering Education program, particularly those undertaking courses in Programmable Logic Controllers (PLC) and pneumatics. The population consisted of all students registered in the PLC Pneumatics course during the academic year, totaling 122 students. These students were distributed across four intact classes.

The sample size in this study was determined based on demographic characteristics and the existing population size. From a total population of 120 students, a sample of 60 students was selected for the study. Simple random sampling was applied to ensure that each member of the population had an equal probability of selection. Proportional random sampling was then used to allocate the sample across the four classes according to their respective population sizes.

The proportional allocation of the sample was calculated using the following formula (X. Wang & Cheng, 2020) :

$$n_i = \frac{N_i}{N} \times n$$

where n_i represents the number of samples from each class, N_i is the population of each class, N is the total population, and n is the total sample size. Based on this calculation, the distribution of participants across classes is presented in Table 1.

Table 1. Research sample

Class	Population	Sample calculation	Sample quantity
1	32	$(32/122) \times 60$	16
2	32	$(32/122) \times 60$	16
3	29	$(29/122) \times 60$	14
4	29	$(29/122) \times 60$	14
Total	122		60

The 60 participants were randomly allocated to either the control or experimental group. The experimental group engaged in activities within an immersive Augmented Reality-integrated virtual laboratory focused on PLC pneumatics. The control group, conversely, was instructed using conventional methods commonly employed in PLC pneumatics courses.

ETHICAL CONSIDERATIONS

This study was conducted in accordance with established ethical principles for educational research. Before data collection, written informed consent was obtained from all participants after they had been informed of the study's purpose and procedures, the voluntary nature of their participation, and their right to withdraw at any time without penalty. To protect participants' privacy and confidentiality, all data were anonymized and used solely for research purposes.

TREATMENT PROCEDURES

Sixty students were randomly divided into an experimental group ($n = 30$) and a control group ($n = 30$). Before the intervention, both groups attended a 60-minute orientation session covering learning

objectives, basic concepts of pneumatic PLCs, and laboratory procedures. A pre-test was administered to assess students' prior knowledge and ensure equal ability between the two groups. The intervention was conducted over four weeks, comprising eight learning sessions held twice a week, each lasting 120 minutes. Both groups received the same duration and scope of material, including PLC basics, ladder logic programming, pneumatic components, electro-pneumatic circuit design, system integration, and troubleshooting procedures. At the end of the intervention, all participants took a 30-minute post-test using the same instrument to evaluate their learning outcomes. To minimize instructor effects, both the experimental and control groups were facilitated by the same lecturer. The lecturer used the same learning objectives, core content, practicum schedule, and assessment procedures for both groups. The main difference between the two groups was the learning treatment used during the practicum preparation stage.

The experimental group followed a step-by-step learning approach that integrated an immersive, Augmented Reality-based virtual laboratory and hands-on laboratory practice. In each practicum session, students first used the virtual laboratory for 30 minutes to observe the system, design ladder logic, assemble virtual control circuits, and test and refine the program through simulation with immediate feedback. This stage provided opportunities for repeated exploration and reinforced understanding before actual implementation. Next, students conducted practice using PLC trainers in the laboratory for 90 minutes to implement and verify the programs they had developed. In contrast, the control group followed the learning process through the lecturer's concept explanations and demonstrations for 30 minutes, then immediately engaged in practice using the PLC trainer for 90 minutes, without first going through the virtual simulation stage. This condition resulted in fewer opportunities for exploration, testing, and program refinement than in the experimental group. Both groups received comparable guidance from the lecturer, feedback, and assessment conditions during the learning process. Therefore, the comparison between the two groups was designed to isolate the effect of ARViLab as the primary treatment variable while maintaining equivalence in learning duration, content coverage, instructor support, and testing procedures.

DATA COLLECTION INSTRUMENTS

This study used three main instruments; the first instrument was a validity questionnaire covering material and media validation. This instrument was developed using a Likert scale and completed by experts following a comprehensive assessment of the learning materials and media. These experts were academics with doctorates and professors who had 25-35 years of experience in PLC, pneumatic media, and learning. This research instrument was adapted from research by Muskhair et al. (2025). Indicators for each aspect of material and media validation instruments are presented in Table 2.

Table 2. The indicators for expert validation of materials and media

Aspect		Indicator
Material aspect	Learning design	The main content, ease of understanding, and depth of the material
	Quality of learning	Enhancing learning motivation, benefits for lecturers and students
	Advantage of learning	Relevance of material, completeness of material, and use of media
Media aspect	Visual quality	Design of media display, text, and images
	Software functionality	Ease of media operation, user instructions, and smooth media operation
	Interactive and communicative	Interactive and communicative

The second instrument was an AR-based practicality questionnaire administered to students in the experimental group. Adapted from Muskhir et al. (2025), the questionnaire measured users' perceptions of ease of use, time efficiency, material presentation, and the perceived benefits of the learning medium. Responses were collected using a Likert scale. The indicators for each aspect of the practicality instrument are presented in Table 3.

Table 3. Indicators of practicality

Aspect	Indicator
Ease of use	Ease of use in operating the application and understanding navigation
Efficiency of Time Use	Measuring the efficiency of time use during the learning process
Material Presentation	Clarity and appropriateness of material presentation in relation to learning objectives
Media Display Quality	The quality of the interface display and visual media in supporting learning comfort

The third instrument was a learning-outcome test administered as both a pre-test and a post-test. Item validity was examined using the biserial correlation coefficient, while reliability was assessed using the Kuder–Richardson 20 (KR-20) coefficient (Shojima, 2022). Item difficulty and discrimination indices were also evaluated. Only items that met the predetermined validity, reliability, difficulty, and discrimination criteria were retained for the final learning-outcome assessment.

DATA ANALYSIS TECHNIQUE

This research aimed to determine whether the ARViLab learning medium developed was effective, feasible, and valid. Using IBM SPSS Statistics 26, quantitative data were analyzed with descriptive and inferential statistics. Table 4 provides an overview of the analytical methods used in this study.

Table 4. Data analysis techniques

Analysis aspect	Technique used	Purpose
Media validity	Aiken's V	Determining expert agreement
Media practicality	Descriptive percentage	Evaluating usability level based on student responses
Learning improvement	Normalized Gain (N-Gain)	Measuring learning effectiveness
Normality testing	Kolmogorov–Smirnov test	Testing data distribution normality
Homogeneity testing	Levene's test	Testing variance equality between groups
Within-group effect	Paired-samples t-test	Analyzing pre-test and post-test differences within each group
Between-group comparison	Independent-samples t-test	Comparing learning outcomes between experimental and control groups
Effectiveness with covariate	Analysis of Covariance (ANCOVA)	Testing treatment effects while controlling for pre-test scores

Media validity was assessed using expert judgment from three subject-matter experts and three media experts. Expert assessments were collected using Likert-scale questionnaires and analyzed with Aiken’s V to assess the level of agreement among experts. The validity evaluation covered instructional design, content quality, learning benefits, visual quality, software functionality, and interactivity. The findings of this analysis were used to confirm the viability of the generated learning medium prior to classroom adoption.

Media practicality was analyzed using student responses collected during the implementation phase. A Likert-scale questionnaire was administered to assess ease of use, time-use efficiency, material presentation, and media display quality. The practicality data were analyzed descriptively and converted into percentage scores to determine the usability level of the learning media (Waskito et al., 2024).

Using a quasi-experimental design with control and experimental groups, researchers evaluated the ARViLab’s efficacy before and after testing. The normalized gain (N-Gain) index enabled quantification of learning progress, assessed by administering tests before and after the learning intervention. N-Gain values were interpreted according to the classification criteria presented in Table 5 (Prasetya et al., 2023).

Table 5. N-Gain classification criteria

N-Gain value	Category
$g \geq 0.70$	High
$0.30 \leq g < 0.70$	Medium
$g < 0.30$	Low

Moreover, paired-samples (within-group) t-tests were employed to investigate changes from pre- to post-intervention within groups (Peng et al., 2025). Assumption tests were run prior to making the between-group comparisons. The research assessed statistical significance using the Kolmogorov-Smirnov test, which checks whether the data are normally distributed, and Levene’s test, which assesses whether the variance is homogeneous. Finally, after the assumption tests were met, an independent-samples t-test was conducted to compare the post-test learning outcomes of the experimental and control groups. Using students’ pre-test scores as covariates, ANCOVA was conducted to examine the effect of the treatment on post-test learning outcomes while controlling for baseline prior knowledge (Yan & Mendoza, 2025). For each test, a significance level of 0.05 was utilized.

RESULT

This study aims to develop a valid, practical, and effective Augmented Reality-Integrated Virtual Laboratory (ARViLab) to improve student learning outcomes in PLC and Pneumatics learning. The development process adapts the simplified Borg and Gall model.

ANALYSIS STAGE

The analysis stage began by identifying learning problems through student surveys and interviews with lecturers teaching PLC and Pneumatics courses. The survey results showed that most students experienced significant difficulties during practical work, caused by limited facilities, the risk of component damage, and a lack of visualization of the interaction between the PLC program and the pneumatic system. This condition was reinforced by lecturers who confirmed that the learning method still relied on conventional media such as PowerPoint presentations, which were considered ineffective for presenting dynamic simulations and real-time interactions. As a result, the existing media was considered monotonous and unable to motivate students, even though students had high digital literacy through smartphone use.

Based on these issues, the needs analysis led to the development of an ARViLab. This proposed solution received support from students and lecturers who expressed the need for innovative media. Both students and lecturers viewed AR technology as the ideal solution to facilitate virtual assembly, programming, and troubleshooting simulations. This media is expected to not only provide a safe and interactive learning experience but also increase motivation, encourage independent learning, and offer flexibility for learning outside class hours.

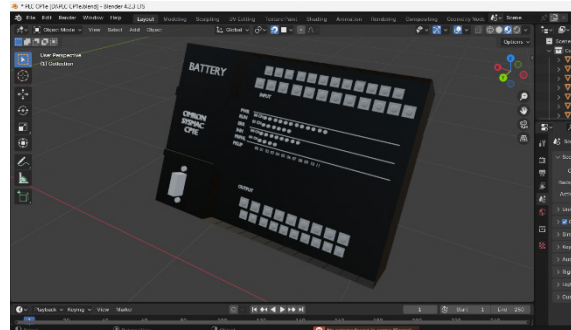
To ensure relevance and focus in development, an analysis of the Semester Learning Plan was also conducted. This analysis successfully mapped materials with high cognitive load and a significant risk of equipment damage, such as basic control circuits that require in-depth procedural understanding. These materials are prioritized for integration into ARViLab. The goal is to help students understand complex concepts visually and interactively in a risk-free environment, so that learning outcomes can be achieved more effectively.

DEVELOPMENT STAGE

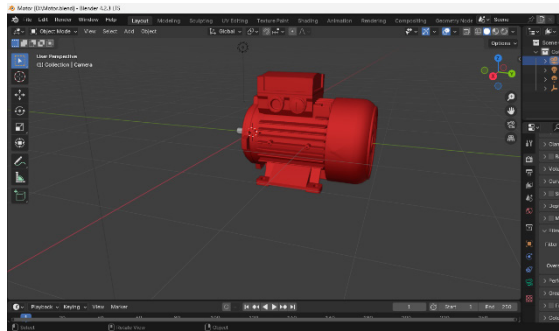
During the development stage, an initial design for the Augmented Reality (AR) application was created, tailored to the findings and requirements from the previous phase. The development stage consisted of designing 3D AR assets, the application structure (storyboard), and the UI (User Interface) display to be shown on the learning media. The three-dimensional (3D) asset design representing the PLC components was developed using Blender. Each model was created to accurately reflect the equipment's physical characteristics, including texture, shape, and scale. The rendering process involved setting the appropriate materials, lighting, and visual effects to ensure realism. To enhance interactivity, the models were animated to demonstrate the cable installation procedure and the system response after the connection was complete. These assets include representations of PLC trainers, magnetic contacts, and three-phase motors (Figure 3). This AR simulation provides students with realistic and interactive tools to understand and practice basic control circuits.



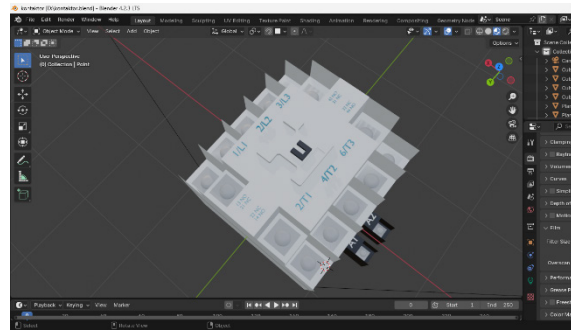
(a) Design of PLC trainers



(b) Design of PLC Omron



(c) Design of three-phase motors



(d) Design of magnetic contacts

Figure 3. The process of creating 3D assets

During the development stage, findings from the analysis stage were transformed into functional products: AR learning media for the PLC & Pneumatics courses. This process involves three main steps: (a) Conceptual and User Interface (UI/UX) design by designing the application user flow, interface layout, and wireframes to ensure an intuitive and interactive learning experience; (b) Digital Asset development by producing all visual components and data needed for simulation. This includes creating 3D models for each component of the PLC and Pneumatics system, designing UI/UX elements, and creating animations that illustrate electrical signal flow and motor rotation; (c) Application Realization and Feature Integration by programming an Augmented Reality-based mobile application. In this step, all digital assets are integrated, and interactive features such as assembly simulations, PLC program execution, and troubleshooting scenarios are implemented. The result of this stage is a functional prototype that is ready for validation.

In Figure 4(a), the main menu display shows several menus that can be accessed, ranging from start, information, and developer to exit, which exits the application. Furthermore, in Figure 4(b), the application usage instruction menu display will direct users to explanations of the menu functions in the application and to the manual menu, which contains complete guidelines on how to use AR-based learning media applications.

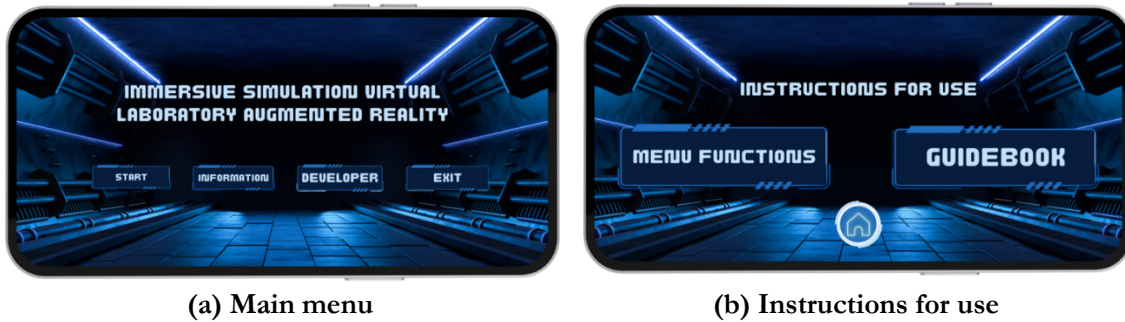


Figure 4. Main menu display and application usage instructions

In Figure 5(a), users can freely select which material in the series they want to work on. Next, after selecting the circuit, users select the menu to determine what they want to work on. Meanwhile, in Figure 5(b), the virtual component menu also includes a scanning component menu, allowing users to display all marker components in 3D and view each component's functions. The component scan menu also provides a demo menu that displays the entire circuit, allowing users to immediately activate it without assembling it first.



Figure 5. Material Menu Display and AR 3D Scan Display

In Figure 6(a), a jobsheet menu is displayed, containing the objectives, implementation steps, and available virtual components. Meanwhile, Figure 6(b) shows a simulation of the motor under PLC control. In the motor rotation simulation feature, users can first assemble the electrical circuit from

the PLC to the electric motor control and also program the PLC. After that, users can see how the simulation of the program and circuit that has been installed works.



(a) Jobsheet menu display

(b) Circuit simulation display

Figure 6. Job sheet menu and circuit simulation display

VALIDATION STAGE

The validation procedure was conducted to determine whether the augmented-reality immersive virtual laboratory was feasible. This was accomplished by evaluating the laboratory's feasibility with a panel of experts that included three subject-matter experts and three media experts. The subject matter experts evaluated the content's accuracy, the curriculum's relevance, and the learning design, whereas the media experts focused on the visual quality, the software's functionality, and the effectiveness of the interaction. Afterward, a quantitative analysis was performed on all evaluation data collected via the questionnaire, using Aiken's V to derive an objective validity index. A comprehensive description of the validity calculation results from both sets of experts, which indicates that the product is feasible, is presented in Table 6 in its entirety.

Table 6. Validation findings from material and media experts

Aspect		Validators			Aiken's V	Average	Category
		1	2	3			
Material aspect	Learning design	0.89	0.97	0.88	0.91	0.85	Valid
	Quality of learning	0.75	0.95	0.85	0.85		
	Advantage of learning	0.88	1.00	0.89	0.92		
Media aspect	Visual quality	0.97	0.95	0.95	0.95	0.95	Valid
	Software functionality	0.97	0.92	0.92	0.93		
	Interactive and communicative	1	0.95	1	0.98		

In general, validation by six experts (three in the subject matter and three in the media) confirmed that the constructed learning media are valid and ready for use. Based on quantitative analysis using Aiken's V, the validation result for the subject-matter aspect averaged 0.85 (Valid), confirming the content's accuracy and suitability. This assessment is significantly reinforced by the validation results for the media aspect, which obtained a higher average score of 0.95 (Valid), proving its superior technical quality, design, and interactivity. Thus, this AR-based Immersive Simulation Virtual Laboratory has been proven to meet the feasibility standards from both crucial perspectives, namely pedagogical and technical feasibility, and is ready to be tested in the next stage.

TESTING AND IMPLEMENTATION STAGE

The purpose of the implementation stage is to test the extent to which and how well AR immersive virtual laboratory learning media works in a real learning environment. This stage employs a quasi-

experimental design with 60 students randomly assigned to two groups: a control group ($n=30$) and an experimental group ($n=30$). The control group received standard conventional learning media in the form of PowerPoint-based teaching, followed by a physical assembly using training kits and printed worksheets. In contrast, the experimental group received ARViLab media as simulation and exercise materials to equip students to test the PLC training kit in real-world laboratory settings. At the last meeting, researchers asked students for feedback on the learning media they had studied during the learning process. Student feedback was used to evaluate the feasibility of using AR-based learning media on mobile devices in PLC Pneumatics courses. In addition, to measure effectiveness, learning outcome data were collected from both groups through pre-tests and post-tests.

The practicality assessment yielded an overall score of 85.61%, placing ARViLab in the “Very Practical” category. As shown in Figure 7, the aspect scores were 88.75% for ease of use, 82.67% for time-use efficiency, 86.29% for material presentation, and 84.75% for media display quality. These results indicate that students generally perceived ARViLab as usable and supportive of the learning process.

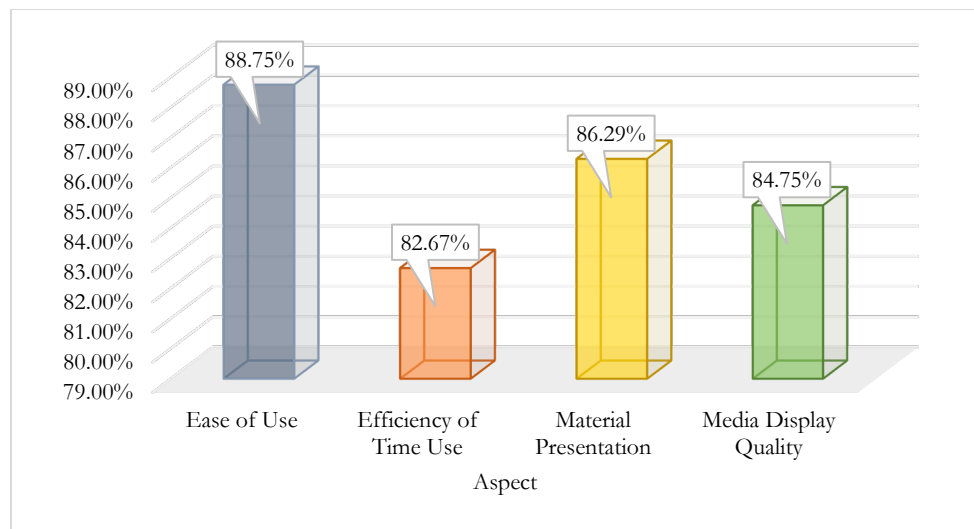


Figure 7. Practicality test results

In addition to collecting hands-on data, this trial gathered learning outcome data for the two groups to analyze effectiveness. To analyze media effectiveness, this research adopted a quasi-experimental design using the Pre-test-Post-test Control Group Design, with two classes as the experimental subjects. First, a pre-test was administered to both groups to measure initial ability. Second, an experiment was conducted with one group by providing treatment in the form of AR-based virtual lab learning, while the other group received conventional learning. Lastly, a post-test was conducted using identical questions and timing for both groups to measure the increase in learning outcomes. The quantitative data were further analyzed using two methods to compute the N-Gain score to assess each group’s effectiveness, as well as a t-test to evaluate differences between the two groups. Table 7 presents the results of the effectiveness analysis based on the N-Gain scores.

Table 7. Findings from effectiveness tests using N-Gain score

Group	Types of test	N	M	SD	N-Gain
Experiment	Pre-test	30	58.20	6.45	0.65 (Medium)
	Post-test	30	85.33	5.24	
Control	Pre-test	30	57.80	6.10	0.29 (Low)
	Post-test	30	70.10	6.15	

The effectiveness results presented in Table 7 show that the experimental group using ARViLab achieved an N-Gain of 0.65, which was classified as Medium, whereas the control group achieved an N-Gain of 0.29, which was classified as Low. These findings indicate that the experimental group experienced greater improvement in learning outcomes than the control group. Thus, the AR-integrated immersive virtual laboratory was more effective in improving students' learning outcomes in PLC-pneumatics education than the conventional learning approach.

The subsequent step involves performing prerequisite tests, including the normality and homogeneity tests, to assess the learning outcomes of the student groups both within and between groups prior to analyzing the efficacy of the two learning media. The normality test assesses whether the distribution of students' learning outcomes in both the control and experimental classes is normal, using the Kolmogorov-Smirnov test. The homogeneity tests aim to determine whether the variation of the data from both samples is homogeneous, utilizing Levene's test. The information is encapsulated in Table 8.

Table 8. Normality and homogeneity test

Variable	Test	Group	K-S		Levene	
			Statistic	p-value	Statistic	p-value
Learning Outcome	Pre-test	Experiment	0.124	0.200	0.345	0.562
		Control	0.118	0.200		
	Post-test	Experiment	0.132	0.185	1.024	0.318
		Control	0.141	0.126		

Table 8 shows that the normality test p-values for the pre- and post-test data in both the control and experimental groups are greater than the significance level of 0.05. The data on students' learning outcomes appear to be normally distributed. The findings of the homogeneity test show that both the pre-test and post-test data have significant values greater than 0.05, at 0.562 and 0.318, respectively. This suggests that there is no significant difference in the data variance between the two groups.

After the assumptions of normality and homogeneity were satisfied, paired-samples and independent-samples t-tests were conducted. The paired-samples t-test examined changes in pre-test and post-test scores within each group, whereas the independent-samples t-test compared post-test scores between the experimental and control groups. The results are presented in Table 9.

Table 9. Summary of paired and independent t-test analysis

Group	Pre-test		Post-test		Paired sample t-test		Independent t-test	
	M	SD	M	SD	t	p	t	p
Experiment	58.20	6.45	85.33	5.24	24.1	< .001	10.32	< .001
Control	57.80	6.10	70.10	6.15	11.4	< .001		

According to Table 9, the paired-samples t-test results indicate that both groups experienced statistically significant improvements in learning outcomes from pre-test to post-test. In the experimental group, the mean score increased from 58.20 (SD = 6.45) to 85.33 (SD = 5.24), with a significant within-group difference ($t = 24.10$, $p < .001$). Similarly, the control group showed an increase from 57.80 (SD = 6.10) to 70.10 (SD = 6.15), which was also statistically significant ($t = 11.40$, $p < .001$). Furthermore, the independent-samples t-test comparing the post-test scores of the two groups showed that the experimental group achieved significantly higher learning outcomes than the control group ($t(58) = 10.32$, $p < .001$). These findings indicate that although both groups improved after the

learning intervention, students who used ARViLab demonstrated substantially higher post-intervention performance than those who received conventional instruction.

Alongside the t-test analyses, an Analysis of Covariance (ANCOVA) was conducted to examine the effect of the learning method on students' post-test scores while controlling for their pre-test scores. Prior to the ANCOVA, the homogeneity of regression slopes assumption was examined and satisfied, indicating that the interaction between group membership and pre-test scores was not statistically significant ($p > .05$). The ANCOVA results are presented in Table 10.

Table 10. Summary of ANCOVA Findings

Source	Df	Mean square	F	p	Partial η^2
Corrected model	2	1960.225	65.451	< .001	.697
Intercept	1	245.120	8.184	.006	.126
Pre-test	1	485.320	16.205	< .001	.221
Group	1	3215.115	107.355	< .001	.653
Error	57	29.948			
Total	60				
Corrected total	59				

Table 10 shows that, after controlling for students' pre-test scores, the effect of group membership on post-test learning outcomes remained statistically significant, $F(1, 57) = 107.355$, $p < .001$, partial $\eta^2 = .653$. This indicates a large treatment effect, with approximately 65.3% of the variance in post-test scores, after accounting for the pre-test covariate, associated with group membership. The results therefore indicate that students in the experimental group who used ARViLab achieved significantly higher adjusted post-test learning outcomes than students in the control group who received conventional instruction.

DISCUSSION

This study aims to design and evaluate ARViLab as a solution to existing problems in conventional PLC and pneumatics teaching. Empirical results show that the media created meet the criteria of validity, practicality, and effectiveness in improving student learning outcomes. Furthermore, the higher N-Gain and post-test scores observed in the experimental group indicate that ARViLab supported greater learning improvement than conventional instruction. The AR approach allows students to directly visualize the interaction between PLC programs and pneumatic actuators in a single integrated learning environment. This differs from conventional methods, where students must divide their attention between job sheets, PC-based logic programs, and separate physical PLC training kits, requiring them to imagine and connect the series of components themselves.

These findings align with prior research indicating that augmented reality can enhance the pedagogical efficacy of educational media by providing clearer and more engaging procedural visualizations (Çeken & Taşkın, 2025). In addition, AR media is also considered practical because it is easily accessible via mobile devices, thereby reducing spatial and temporal barriers in laboratory learning (Singh & Ahmad, 2024). Furthermore, the findings of this research corroborate that AR can substantially enhance knowledge retention and learning outcomes in the fields of science and engineering (Liu et al., 2025; Mokmin et al., 2024; Suhail et al., 2024). By providing opportunities for repeated exploration, students gain a richer learning experience than with lectures or limited laboratory methods. This significant improvement in learning outcomes is also consistent with experiential learning theory and previous research stating that immersive technology can reduce cognitive load when learning complex systems (Altmeyer et al., 2024; Álvarez-Marín et al., 2025; Coştu, 2025). The findings reinforce

the study by Suhail et al. (2024), which reported increased student engagement through AR visualization. Furthermore, these results support Sanzana et al.'s (2024) argument that virtual laboratories provide a risk-free environment for repeated experimentation, thereby strengthening students' procedural understanding of industrial control systems.

The main contribution of this research is the innovative integration of PLC and pneumatics in AR, which has rarely been explored in previous research, as most previous studies have only emphasized the visualization of electronic or mechanical components separately (Anwar et al., 2024; Muskhir et al., 2024; Waskito et al., 2024). A comparison of current and previous research shows that passive AR applications identified in previous research gaps display only 3D models without interaction, whereas ARViLab provides a holistic ecosystem where students can assemble and test PLC ladder logic in real time. The use of realistic 3D assets (such as three-phase motors and magnetic contacts) also helps bridge the gap between abstract theory and physical application. This spatial ability is important in electrical engineering (Habibi & Fieschko, 2020), where understanding schematic diagrams must translate into actual cable installations. This addresses the limitations identified by Sukardjo et al. (2023) and Widodo et al. (2024) concerning the separation between software simulation and mechanical response. By virtually integrating the behavior of pneumatic actuators, this medium provides a more complete systemic understanding, changing students' perception from simply observing to "doing" (learning by doing).

IMPLICATIONS

From a practical perspective, the implementation of ARViLab offers a scalable solution to overcome the resource limitations faced by universities and vocational institutions. By moving the initial stages of practice to a virtual environment, campuses can overcome obstacles such as limited PLC Pneumatic training kits and high physical laboratory maintenance costs. This means that campuses can improve the efficiency of the student-to-equipment ratio, so that time in physical laboratories can be focused on advanced problem solving rather than just basic assembly. In addition, the portability of the mobile AR system supports flexible learning, allowing pneumatic PLC learning to be accessed anywhere, anytime.

However, the implementation of ARViLab should not be interpreted as an automatically low-cost solution in every institutional context. Although AR-based virtual laboratories may reduce reliance on expensive physical equipment, their adoption still requires careful consideration of initial development costs, compatibility with mobile devices, software maintenance, technical support, lecturer training, and long-term sustainability. The actual cost-effectiveness of ARViLab may depend on the scale of implementation, the availability of students' devices, the institution's digital infrastructure, and the institution's ability to maintain and update the AR content over time. Therefore, institutions need to conduct a contextual cost-benefit analysis before adopting ARViLab as a regular component of PLC-pneumatics learning.

Successful implementation also requires adequate technical and pedagogical preparation. From a technical perspective, institutions need to ensure that students have access to compatible smartphones or other mobile devices, that the application runs smoothly across different hardware specifications, and that technical support is available when users encounter installation, scanning, or performance issues. From a pedagogical perspective, lecturers need training not only in operating the application but also in integrating ARViLab into lesson plans, practicum procedures, assessment activities, and feedback mechanisms. Thus, ARViLab is best positioned as a complementary learning environment that prepares students for physical laboratory practice, rather than as a complete replacement for hands-on laboratory experience.

LIMITATIONS

Although ARViLab media shows potential to improve student learning outcomes in pneumatic PLC learning, several limitations should be considered when interpreting these findings. First, the study

involved a relatively small and homogeneous sample from a single study program and institution, namely Electrical Engineering Education at Universitas Negeri Padang. Therefore, the generalization of the findings to broader populations, different institutions, vocational education contexts, or other engineering disciplines should be made with caution. Future studies involving larger and more diverse samples are needed to strengthen the external validity of the findings.

Second, although the same lecturer facilitated both the experimental and control groups to minimize instructor effects, differences in classroom dynamics, student motivation, interaction patterns, and responses to the learning media may still have influenced the results. In addition, the implementation of ARViLab depended on students' mobile devices, which may vary in hardware specifications, screen size, camera quality, and operating system compatibility. Students' prior familiarity with AR, VR, or mobile-based learning may also have affected how easily they adapted to the learning media.

Third, the adoption of ARViLab requires institutional readiness, including compatible devices, lecturer training, technical support, software maintenance, and sustainable digital infrastructure. Therefore, although ARViLab may reduce dependence on physical laboratory equipment, its cost-effectiveness may vary with institutional context and the scale of implementation. Finally, this study primarily measured short-term learning outcomes using pre-test and post-test scores. Longitudinal studies are needed to examine long-term retention, skill transfer, and the application of PLC-pneumatics competence in real industrial contexts.

FUTURE RESEARCH DIRECTIONS

Based on the limitations identified, future research should focus on several strategic developments. Given that this study is still limited to evaluating short-term learning outcomes, conducting a longitudinal study is highly recommended to measure students' retention of technical skills over a longer period. Further development should also explore the use of multi-user Virtual Reality to simulate team collaboration and conduct PLC practices as they occur in real industry settings. In addition, integrating Artificial Intelligence to provide adaptive, real-time feedback on student errors will elevate the system from a simulation tool to an intelligent virtual tutor.

CONCLUSION

This study successfully developed an Augmented Reality (AR)-integrated virtual laboratory, namely ARViLab, to address the limitations of conventional PLC and pneumatics learning. The development process was carried out systematically using a modified Borg and Gall model, producing learning media that were valid, practical, and effective, as evidenced by expert validation, student practicality responses, and empirical learning outcome tests. The expert validation results showed that ARViLab met the feasibility criteria in both material and media aspects. In contrast, the practicality results indicated that students perceived the application as easy to use, useful, and supportive of the learning process. The quasi-experimental findings also showed that students in the experimental group demonstrated greater improvement in learning outcomes than those in the control group, as reflected in the N-Gain, paired-samples t-test, independent-samples t-test, and ANCOVA results.

The main contribution of this study lies in the development and evaluation of an interactive, system-level AR-integrated virtual laboratory that combines component visualization, virtual circuit assembly, PLC ladder logic testing, and pneumatic actuator simulation within a single learning environment. Unlike AR applications that mainly focus on passive visualization, ARViLab provides students with opportunities to observe, construct, test, revise, and understand PLC-pneumatics systems before conducting physical laboratory practice. Through realistic 3D assets, simulation-based interaction, and guided virtual practice, ARViLab helps transform abstract PLC and pneumatics concepts into more concrete learning experiences. Therefore, this study contributes not only to the development of AR-based instructional media but also to the empirical understanding of how immersive technology can support practical skill development in engineering education.

Nevertheless, the findings should be interpreted with caution because this study was conducted with a relatively limited and homogeneous sample from a single institution. The implementation of ARViLab also depends on students' mobile device compatibility, lecturer readiness, technical support, institutional infrastructure, and the sustainability of application maintenance. In addition, the study primarily measured short-term learning outcomes, so it does not yet provide sufficient evidence on long-term retention, the transfer of skills to real-world industrial contexts, or sustained practical competence. Future research should therefore involve broader, more diverse samples, conduct cost-benefit and implementation analyses, examine potential instructor effects, and evaluate the long-term impact of ARViLab on students' technical competence. Further development may also integrate Virtual Reality (VR), multi-user collaboration, and Artificial Intelligence (AI)-based adaptive feedback to create a more intelligent and collaborative immersive learning environment for PLC-pneumatics education.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to all individuals and parties who contributed to and supported the completion of this research. The authors also gratefully acknowledge Universitas Negeri Padang for providing the facilities and institutional support required for the implementation of this study. Special appreciation is extended to the Directorate of Research and Community Service, Directorate General of Research and Development, Ministry of Higher Education, Science, and Technology of the Republic of Indonesia, for providing financial support for this research under Research Implementation Contract No. 088/C3/DT.05.00/PL/2025. The authors sincerely appreciate all participants and colleagues whose assistance and contributions were valuable throughout the research process.

REFERENCES

- Adel, A. (2024). The convergence of intelligent tutoring, robotics, and IoT in smart education for the transition from Industry 4.0 to 5.0. *Smart Cities*, 7(1), 325–369. <https://doi.org/10.3390/smartcities7010014>
- Aggarwal, R., Gupta, P., Singh, S., & Bala, R. (2024). *Augmented reality and the future of education technology*. IGI Global. <https://doi.org/10.4018/979-8-3693-3015-9>
- Ali, A., Hamza, A., & Saleh, H. (2024). Risk management strategies in medical laboratory practice. *International Journal of Medical Laboratory Research*, 9(2), 18–32. <https://doi.org/10.35503/IJMLR.2024.9203>
- Alia, Y., & El Harmouzi, N. (2024). Industrial policies in the 21st century: The 4th generation of industrial revolutions. *International Journal of Accounting, Finance, Auditing, Management and Economics*, 5(7), 335–350. <https://doi.org/10.5281/zenodo.12740233>
- Altmeyer, K., Brünken, R., Kuhn, J., & Malone, S. (2024). The role of cognitive learner prerequisites for cognitive load and learning outcomes in AR-supported lab work. *Education Sciences*, 14(11), 1161. <https://doi.org/10.3390/educsci14111161>
- Álvarez-Marín, A., Paredes-Velasco, M., Velázquez-Iturbide, J. Á., & Palma-Chilla, L. (2025). Insights into usability, academic outcomes, and emotional responses in an AR-Interactive learning environment. *Interactive Learning Environments*, 33(4), 3147–3161. <https://doi.org/10.1080/10494820.2024.2440862>
- Álvarez-Marín, A., & Velázquez-Iturbide, J. A. (2022). Augmented reality and engineering education: A systematic review. *IEEE Transactions on Learning Technologies*, 14(6), 817–831. <https://doi.org/10.1109/TLT.2022.3144356>
- Anwar, M., Rahmawati, Y., Yuniarti, N., Hidayat, H., & Sabrina, E. (2024). Leveraging augmented reality to cultivate higher-order thinking skills and enhance students' academic performance. *International Journal of Information and Education Technology*, 14(10), 1405–1413. <https://doi.org/10.18178/ijiet.2024.14.10.2171>

- Çeken, B., & Taşkın, N. (2025). Examination of multimedia learning principles in augmented reality and virtual reality learning environments. *Journal of Computer Assisted Learning*, 41(1), e13097. <https://doi.org/10.1111/jcal.13097>
- Coştu, F. (2025). Exploring augmented reality (AR) in science education: Perspectives from gifted students. *The Journal of Educational Research*, 118(1), 19–36. <https://doi.org/10.1080/00220671.2024.2431681>
- Criollo-C, S., Abad-Vásquez, D., Martic-Nieto, M., Velásquez-G, F. A., Pérez-Medina, J.-L., & Luján-Mora, S. (2021). Towards a new learning experience through a mobile application with augmented reality in engineering education. *Applied Sciences*, 11(11), 4921. <https://doi.org/10.3390/app11114921>
- Doerner, R., & Horst, R. (2022). Overcoming challenges when teaching hands-on courses about Virtual Reality and Augmented Reality: Methods, techniques and best practice. *Graphics and Visual Computing*, 6, Article 200037. <https://doi.org/10.1016/j.gvc.2021.200037>
- Esen, Y. E., Çetincan, B. K., Yayan, K., Gürlek, H. G., & Yayan, U. (2025). XR-driven robotic system training for occupational health, safety, and maintenance. *IEEE Access*, 13, 61708–61727. <https://doi.org/10.1109/ACCESS.2025.3556699>
- Fortuna, A., Prasetya, F., Samala, A. D., Andriani, W., Rawas, S., Amri, R. S., Chai, H., Compagno, M., Abbasinia, S., & Nabawi, R. A. (2024). Enhancing occupational health and safety education: A mobile gamification approach in machining workshops. *International Journal of Information and Education Technology*, 14(9), 1227–1238. <https://doi.org/10.18178/ijiet.2024.14.9.2152>
- Gauthama, W., Hendra, O., Aswia, P. R., & Amalia, D. (2025). Updating aircraft maintenance education for the modern era: A new approach to vocational higher education. *Higher Education, Skills and Work-Based Learning*, 15(1), 46–61. <https://doi.org/10.1108/HESWBL-11-2023-0314>
- George, A. S. (2024). The fourth industrial revolution: a primer on industry 4.0 and its transformative impact. *Partners Universal Innovative Research Publication*, 2(1), 16–40. <https://doi.org/10.5281/zenodo.10671872>
- Habibi, C., & Fieschko, D. (2020, June). PLC training in first year Electrical Engineering program. Paper presented at the ASEE Virtual Annual Conference Content Access. <https://doi.org/10.18260/1-2--35060>
- Irfan, M. A., Irshad, Y., Khan, W., Iqbal, A., & Khalil, A. (2024). Augmented reality in education: An immersive experience centered on educational content. In S. K. Gupta & J. Rosak-Szyrocka (Eds.), *Innovation in the University 4.0 System based on smart technologies* (pp. 116–142). Chapman and Hall/CRC. <https://doi.org/10.1201/9781003425809-8>
- Iswan, R. A. (2024). Development of a virtual laboratory platform to enhance chemistry practical learning in higher education. *Journal of Education Innovation and Curriculum Development*, 2(3), 90–98. <https://journals.iarn.or.id/index.php/educur/article/view/442>
- Kiryakova, G. (2020). The immersive power of augmented reality. In Y. Rybarczyk (Ed.), *Human 4.0 - From biology to cybernetic*. IntechOpen. <https://doi.org/10.5772/intechopen.92361>
- Kovalchuk, V. I., Maslich, S. V., & Movchan, L. H. (2023). Digitalization of vocational education under crisis conditions. *Educational Technology Quarterly*, 2023(1), 1–17. <https://doi.org/10.55056/etq.49>
- Kulkarni, R., & Harne, R. (2024). Adoption and usage of augmented reality-based virtual laboratories tool for engineering studies. *Journal of Information Technology Education: Innovations in Practice*, 23, 010. <https://doi.org/10.28945/5351>
- Lampropoulos, G., del Bosque, A., Fernández-Arias, P., & Vergara, D. (2025). Augmented reality in engineering education: a bibliometric review. *Information*, 16(10), 859. <https://doi.org/10.3390/info16100859>
- Liu, P., Yang, Z., Huang, J., & Wang, T.-K. (2025). The effect of augmented reality applied to learning process with different learning styles in structural engineering education. *Engineering, Construction and Architectural Management*, 32(6), 3727–3759. <https://doi.org/10.1108/ECAM-06-2023-0596>
- Lovrec, D. (2019, November). Education in the field of fluid power technology-challenges, opportunities and possibilities. *Proceedings of 2019 International Conference on Hydraulics and Pneumatics-HERVEX, Băile Govora, Romania*, 12–23. <https://fluidas.ro/hervex/proceedings2019/pp.12-23.pdf>

- Margheritti, S., Marcucci, S., & Miglioretti, M. (2025). Bridging the gaps: examining the impact of technology-based active learning in workplace safety training through a systematic literature review. *Safety*, 11(1), 5. <https://doi.org/10.3390/safety11010005>
- Mokmin, N. A. M., Hanjun, S., Jing, C., & Qi, S. (2024). Impact of an AR-based learning approach on the learning achievement, motivation, and cognitive load of students on a design course. *Journal of Computers in Education*, 11(2), 557–574. <https://doi.org/10.1007/s40692-023-00270-2>
- Muskhir, M., Luthfi, A., Effendi, H., Jalinus, N., Samala, A. D., & Slavov, V. (2025). Can mobile-based augmented reality improve learning in electrical circuit education? *International Journal of Information and Education Technology*, 15(3), 595-604. <https://doi.org/10.18178/ijiet.2025.15.3.2268>
- Muskhir, M., Luthfi, A., Sidiq, H., & Fadillah, R. (2024). Development of augmented reality based interactive learning media on electric motor installation subjects. *JOIV: International Journal on Informatics Visualization*, 8(4), 2097–2103. <https://doi.org/10.62527/joiv.8.4.2256>
- Neffati, O. S., Setiawan, R., Jayanthi, P., Vanithamani, S., Sharma, D. K., Regin, R., Mani, D., & Sengan, S. (2021). An educational tool for enhanced mobile e-learning for technical higher education using mobile devices for augmented reality. *Microprocessors and Microsystems*, 83, 104030. <https://doi.org/10.1016/j.micpro.2021.104030>
- Peng, C., Gu, W., & Jiang, L. (2025). Effects of mobile-assisted language learning (mall)-delivered explicit metacognitive intervention on Chinese EFL students' receptive skills and metacognitive awareness. *Journal of Computer Assisted Learning*, 41(5), e70125. <https://doi.org/10.1111/jcal.70125>
- Prasetya, F., Fortuna, A., Samala, A. D., Fajri, B. R., Efendi, F., & Nyamapfene, A. (2023). Effectiveness of distance learning computer numerical control based on virtual laboratory using a metaverse platform to improve students' cognitive ability and practice skills. *International Journal of Interactive Mobile Technologies*, 17(24), 4–21. <https://doi.org/10.3991/IJIM.V17I24.45019>
- Rafa, R. R., Rahman, T., Kobir, M. H., Yang, Y., & Deb, S. (2024). Enhancing experiential learning through virtual reality: System design and a case study in additive manufacturing. *Human Factors and Ergonomics in Manufacturing & Service Industries*, 34(6), 649–666. <https://doi.org/10.1002/hfm.21055>
- Rizvi, S. A. Q., Rehman, U., Cao, S., & Moncion, B. (2025). Exploring technology acceptance of flight simulation training devices and augmented reality in general aviation pilot training. *Scientific Reports*, 15, Article 2302. <https://doi.org/10.1038/s41598-025-85448-7>
- Romano, M., Díaz, P., & Aedo, I. (2023). Empowering teachers to create augmented reality experiences: The effects on the educational experience. *Interactive Learning Environments*, 31(3), 1546–1563. <https://doi.org/10.1080/10494820.2020.1851727>
- Sanzana, M. R., Abdulrazic, M. O. M., Wong, J. Y., Karunagharan, J. K., & Chia, J. (2024). Gamified virtual labs: shifting from physical environments for low-risk interactive learning. *Journal of Applied Research in Higher Education*, 16(1), 208–221. <https://doi.org/10.1108/JARHE-09-2022-0281>
- Shamsuzzaman, H. M., Mosleuzzaman, M., Mia, A., & Nandi, A. (2024). Cybersecurity risk mitigation in industrial control systems analyzing physical hybrid and virtual test bed applications. *Academic Journal on Artificial Intelligence, Machine Learning, Data Science and Management Information Systems*, 1(1), 19–39.
- Shi, H., Karim, A. A., Husnin, H., & Hua, X. (2026). Design and development of AR instructional materials for light and shadow Art. *Journal of Information Technology Education. Innovations in Practice*, 25, 3. <https://doi.org/10.28945/5702>
- Shojima, K. (2022). *Test data engineering*. Springer. <https://doi.org/10.1007/978-981-16-9986-3>
- Singh, G., & Ahmad, F. (2024). An interactive augmented reality framework to enhance the user experience and operational skills in electronics laboratories. *Smart Learning Environments*, 11, Article 5. <https://doi.org/10.1186/s40561-023-00287-1>
- Singh, G., Mantri, A., Sharma, O., Dutta, R., & Kaur, R. (2019). Evaluating the impact of the augmented reality learning environment on electronics laboratory skills of engineering students. *Computer Applications in Engineering Education*, 27(6), 1361–1375. <https://doi.org/10.1002/cae.22156>

- Suhail, N., Bahroun, Z., & Ahmed, V. (2024). Augmented reality in engineering education: Enhancing learning and application. *Frontiers Virtual Real*, 5, 1461145 <https://doi.org/10.3389/frvir.2024.1461145>
- Sukardjo, M., Khasanah, U., Turibius, S. T., Khaerudin, & Setiawan, B. (2023). Virtual laboratory design for learning electro-pneumatic practices in vocational high schools. *European Journal of Educational Research*, 12(2), 719–737. <https://doi.org/10.12973/eu-jer.12.2.719>
- Šulc, J., Vidicki, P., Reljić, V., Milenković, I., & Dudić, S. (2023). Augmented reality as an aid to collaborative and autonomous learning in engineering education. *Journal of Scientific and Industrial Research*, 82(7), 736–744. <https://doi.org/10.56042/jsir.v82i07.2150>
- Triatmaja, A. K., Budiastuti, P., & Rismarinandyo, M. Y. (2024). Development of an IoT-based PLC trainer: Bridging the practical divide in industrial automation education. *International Journal of Educational Management and Innovation*, 5(1), 39–52. <https://doi.org/10.12928/ijemi.v5i1.9732>
- Vilches, M., Vargas, H., de la Torre, L., & Heradio, R. (2025). Scalable hybrid laboratories: Application in industrial automation. *Results in Engineering*, 26, 105342. <https://doi.org/10.1016/j.rineng.2025.105342>
- Volansky, K. J. (2020). What are best practices to teach “hands-on” skills in a blended environment? *Journal of Applied Learning and Teaching*, 3(1), 80–89. <https://doi.org/10.37074/jalt.2020.3.1.6>
- Wang, K., Scott, J., & Jollands, M. (2025). Enhancing analog electronics education in undergraduate degrees through digital spine-enabled hybrid passive-active learning design. *IEEE Access*, 13, 104679–104691. <https://doi.org/10.1109/ACCESS.2025.3574639>
- Wang, X., & Cheng, Z. (2020). Cross-sectional studies: Strengths, weaknesses, and recommendations. *CHEST*, 158, S65–S71. <https://doi.org/10.1016/j.chest.2020.03.012>
- Waskito, Fortuna, A., Prasetya, F., Ema, R., Wulansari, Nabawi, R. A., & Luthfi, A. (2024). Integration of mobile augmented reality applications for Engineering mechanics learning with interacting 3D objects in Engineering education. *International Journal of Information and Education Technology*, 14(3), 354–361. <https://doi.org/10.18178/ijiet.2024.14.3.2057>
- Widodo, C., Tamrin, A. G., & Cahyono, B. T. (2024). Augmented Reality (AR)-based learning media to overcome pneumatic and hydraulic learning problems in the 21st century learning era. *Prosiding Senadika: Seminar Nasional Akademik*, 1(1), 523–534. <https://unars.ac.id/ojs/index.php/SENADIKA/article/view/5845>
- Wulansari, R. E., Fortuna, A., Marta, R., Primawati, P., Masek, A., Kaya, D., Prasetya, F., Sakti, R. H., Luthfi, A., & Rizki, I. A. (2024). Revolutionizing learning: Unleashing the power of technology gamification-augmented reality in vocational education. *TEM Journal*, 13(3), 2384–2397. <https://doi.org/10.18421/TEM133-65>
- Yan, Z., & Mendoza, N. B. (2025). Learning and practicing simultaneously: the synergistic effect of online self-assessment diaries and teacher self-assessment instruction on learning and growth mindset. *Assessment in Education: Principles, Policy & Practice*, 32(3), 276–298. <https://doi.org/10.1080/0969594X.2025.2534134>

ACKNOWLEDGMENT

Acknowledgments for financial support for this research, which was funded by the Ministry of Education, Culture, Research, and Technology, Directorate General of Higher Education, Research, and Technology, as well as the Directorate of Research, Technology, and Community Service, with contract number: 088/C3/DT.05.00.PL/2025, conducted at Universitas Negeri Padang.

AUTHORS



Dr Mukhlidi Muskhir graduated with a Bachelor of Vocational Education in Electrical Engineering from Universitas Negeri Padang in 1998, then pursued a Master of Computer Science at Universitas Gadjah Mada in 2001, graduating in 2003. He continued his doctoral studies in 2011, earning a Doctorate in Vocational Technology Education from Universitas Negeri Yogyakarta and graduating in 2017. He is currently a lecturer in the Department of Electrical Engineering at the Faculty of Engineering, Universitas Negeri Padang. His research interests include the research-based learning model, the self-directed learning model, and curriculum development in vocational technology education, as well as virtual reality, augmented reality, mobile learning, computer science, and robotics.



Afdal Luthfi graduated with a Bachelor's degree in Vocational Education in Electrical Engineering from Universitas Negeri Padang in 2022, and continued with a Master of Technical Vocational Education in Electrical Engineering at Universitas Negeri Padang, graduating in 2024. He continued his doctoral studies in 2026, earning a degree in Computer Science from Universitas Gadjah Mada. He works as an Assistant Professor in the Department of Electrical Engineering, in the Faculty of Engineering, Universitas Negeri Padang. His research interests include educational technology, emerging technologies in education, vocational education and training, virtual reality, augmented reality, mobile learning, computer science, and robotics.



Dr Hansi Effendi has been a senior lecturer in the Electrical Engineering Department in the Faculty of Engineering, Universitas Negeri Padang, since 2002. His research focuses on ICT-based learning models, blended learning, mobile learning, and artificial intelligence.



Dr Dedy Irfan is a lecturer and researcher at the Department of Electronic Engineering, Faculty of Engineering, Universitas Negeri Padang (UNP). He earned his doctoral degree (PhD) in Education Sciences from the same university. His research focuses on Technical and Vocational Education and Training (TVET), pedagogical innovation, and technology integration in learning.



Roni Eka Rahmat received his Bachelor's degree in Electrical Engineering Education from Universitas Negeri Padang, Indonesia, in 2019 and his Master's degree in Vocational and Technology Education from Universitas Negeri Yogyakarta, Indonesia, in 2024. He is currently a Lecturer in the Department of Information and Communication Technology Education, Faculty of Tarbiyah and Teacher Training, UIN Sjech M. Djamil Djambek Bukittinggi, Indonesia. He is also a tutor in the Information Systems Program at Universitas Terbuka. His research interests include Educational Technology, Vocational Education and Training (TVET), technology acceptance models, artificial intelligence in education, virtual reality, e-learning, and digital learning innovation.