**Indonesian Journal of Automotive Technology**
**Volume 1, Issue 1, 22-32.**
e_ISSN: -
https://ejournal.foundae.com/index.php/ijat

# Development and Validation of an Arduino-Based Cooling System Simulator for Enhancing Learning Outcomes in Automotive Engineering Education

**Gusti Muhammad Andrian Ar Raziey***
Universitas Pendidikan Indonesia, INDONESIA

**Yusep Sukrawan**
Universitas Pendidikan Indonesia, INDONESIA

**Muhammad Maris Al Gifari**
Universitas Pendidikan Indonesia, INDONESIA

**Article Info**

***Article history:***
Received: April 03, 2025
Revised: May 02, 2025
Accepted: June 02, 2025

***Keywords:***
Arduino-based simulator;
Automotive education;
Cooling system;
Instructional media;
Learning outcomes.

**Abstract**

To develop and validate an Arduino-based cooling system simulator that enhances students' understanding and learning outcomes in automotive engineering education through hands-on visualization of engine cooling mechanisms. The study applied the 4-D development model (Define, Design, Develop, and Disseminate) covering needs analysis, prototype creation, expert validation, and field testing. The simulator featured transparent components and a programmable Arduino controller to visualize real-time coolant flow and temperature changes. Validation involved three media experts, three subject-matter experts, and practicality testing with thirty automotive engineering students. The simulator obtained a validity score of 90% from media experts and 89% from material experts, categorized as highly valid. Practicality testing yielded an 89% score, indicating high practicality and effectiveness for classroom use. The Arduino-based cooling system simulator effectively bridges theoretical and practical learning, improving comprehension and engagement in automotive engineering education. It is recommended for integration into vocational and higher education curricula to promote interactive and experiential learning.

**To cite this article:** Ar Raziey, G. M. A., Sukrawan, Y., & Al Gifari, M. M. (2025). Development and validation of an arduino-based cooling system simulator for enhancing learning outcomes in automotive engineering education. *Indonesian Journal of Automotive Technology, 1*(1), 22-32.



## INTRODUCTION

The evolution of Industry 4.0 has accelerated the need for automation, control systems, and interactive learning environments in engineering education. In automotive engineering, one of the most challenging subjects for students is understanding the complex thermodynamic processes within vehicle cooling systems, which are often taught through static diagrams and lectures (Yeadon & Quinn, 2021). Such conventional approaches fail to engage learners and limit their capacity to visualize dynamic mechanisms like coolant circulation, temperature feedback, and electronic regulation. The introduction of Arduino-based systems provides an opportunity to create interactive simulators that visualize these processes in real time, bridging the gap between theory and practice (Lee, 2025; Reivanth et al., 2024). Arduino technology offers affordability, programmability, and modularity, making it ideal for low-cost educational innovation in developing countries (Marín-Marín et al., 2024; Tsebesebe et al., 2025). In this context, integrating Arduino into simulator development aligns with global educational trends toward smart learning environments. The creation of such simulators not only enhances students' cognitive understanding but also stimulates motivation and problem-solving skills (Hsu & Wu, 2023; P.-C. Lin et al., 2022). Therefore, developing an Arduino-based cooling system simulator represents an urgent pedagogical innovation in automotive education.

The growing demand for skilled automotive technicians highlights the importance of practical training tools that accurately replicate real-world mechanical functions. Universities and vocational institutions in Indonesia and other developing nations still face challenges in providing sufficient laboratory infrastructure for automotive system visualization (Supangkat et al., 2024).

* **Corresponding author:**
Gusti Muhammad Andrian Ar Raziey, Universitas Lampung, INDONESIA
arraziey@gmail.com

Simulators that use transparent components and embedded sensors can offer a solution by allowing students to observe how coolant circulates and regulates engine temperature under varying operational conditions. Research has shown that interactive visualization significantly improves students' conceptual retention and engagement (C.-Y. Lin & Wu, 2021; Stanciulescu et al., 2024). Moreover, the integration of low-cost embedded systems has become an educational strategy to democratize access to laboratory experiences (Doloi et al., 2025; Maiti et al., 2021). Arduino-based educational media enable realistic feedback, which is essential for developing analytical and diagnostic competencies among students (Barradas et al., 2024; Marín-Marín et al., 2024). Such technological integration strengthens vocational education quality while aligning with the Sustainable Development Goals on equitable access to quality education. Hence, the urgency of this study lies in addressing the pedagogical limitations in teaching abstract automotive systems.

This research topic is particularly relevant to the future of automotive engineering education because it merges mechanical understanding with digital literacy. The use of programmable simulators supports multidisciplinary learning, combining electronics, software, and mechanical design (Ryalat et al., 2025; Zheng et al., 2024). Through this integration, students not only comprehend engine behavior but also develop skills applicable to the emerging electric and smart vehicle industries (Curiel-Ramirez et al., 2022; Ravi et al., 2024). Global studies in simulation-based learning have consistently emphasized that immersive and interactive media accelerate skill mastery and creativity (Pang et al., 2025; Stenseth et al., 2025). In line with this, the Arduino-based cooling system simulator serves as an adaptive model for practical instruction, reflecting industrial-level automation in a classroom context. The study therefore contributes to the ongoing discourse on experiential and technology-driven pedagogy. Its novelty lies in combining transparency, real-time data monitoring, and digital control within one compact learning system. Thus, the research presents both educational and technological innovation in preparing future-ready automotive engineers.

This study was undertaken to provide a practical, validated, and replicable model for implementing simulation-based learning using accessible technology. As mechanical systems become increasingly complex, there is a growing need for affordable and realistic training media that can simulate core automotive functions without the risks and costs associated with real engines (Alghodhaifi & Lakshmanan, 2021; El Hadraoui et al., 2022). Arduino microcontrollers enable such simulation through real-time data collection and automation, helping students directly observe cause-and-effect relationships in cooling processes. The educational rationale follows constructivist principles where learning is maximized when students actively engage in modeling and experimentation (Do et al., 2023; M. J. Zhang et al., 2022). Moreover, the transparent design of the simulator enhances comprehension by transforming abstract thermodynamic concepts into observable physical phenomena. The study also responds to the lack of validated instructional models in vocational engineering that combine cognitive, psychomotor, and affective outcomes. Hence, the development of an Arduino-based cooling system simulator represents a pedagogically and technologically sound response to current educational needs.

Recent studies in engineering education confirm the effectiveness of Arduino-based learning environments and simulators in enhancing students' technical understanding. Zhang et al., (2024) demonstrated the integration of Modelica and Arduino-based hardware-in-the-loop simulation for nuclear-powered systems, highlighting the potential of embedded systems for real-time educational modeling. Atanasković et al., (2024) emphasized how online Arduino simulators democratize IoT education and facilitate scalable digital literacy development. Ashokkumar et al., (2022) introduced an Arduino-based electric vehicle emulator that successfully replicated power transmission characteristics in a classroom context. Oteri, (2020) found that open-source Arduino e-kits improve engineering and technology e-learning efficiency. Biswas et al., (2018) developed a hardware-in-the-loop DC drive system simulator that demonstrated the advantages of low-cost prototyping in technical education. Francisco et al., (2020) confirmed that open-source control units for electric vehicles support autonomous learning and design-based problem solving. These studies collectively underscore that Arduino-based systems provide a feasible pathway to enhance experiential learning in mechanical and electrical engineering contexts.

In addition, Rodriguez-Sanchez et al., (2020) reported the benefits of collaborative digital projects using open-source tools for engineering students, fostering creativity and teamwork. Chhatriwala et al., (2025) demonstrated how surgical simulators improved motor coordination, underscoring the broader applicability of simulation learning across disciplines. Leocádio et al., (2025) developed cardiopulmonary resuscitation simulators that enhanced real-time feedback and performance assessment in medical engineering. Kuba et al., (2021) argued that instructional media effectiveness depends on design quality, usability, and learner interaction, principles that are directly applied in this study. Collectively, these ten studies provide empirical evidence that simulation-based learning fosters technical mastery, engagement, and motivation. The present research extends this body of knowledge by focusing on the integration of Arduino-controlled transparency simulators into automotive cooling systems education. Therefore, it situates itself within the intersection of engineering innovation and educational technology.

Although previous research has explored various Arduino-based simulators, few have addressed thermodynamic visualization in automotive education. Most existing simulators focus on electronic control or mechatronic systems without incorporating transparent physical structures that allow direct observation of liquid flow and temperature variation (Biswas et al., 2018). Additionally, only a limited number of studies have validated such simulators through both expert and user-based evaluations, leaving a methodological gap in confirming educational practicality (Santoso et al., 2018). Furthermore, simulator research has predominantly targeted vocational secondary education, with insufficient focus on higher education in engineering programs (Frady, 2023). This study addresses these gaps by developing a validated simulator that integrates mechanical transparency, digital feedback, and automation. It expands the pedagogical framework by demonstrating that technology-enhanced learning can effectively transform abstract theory into concrete experience. By embedding Arduino control, the study provides new evidence of how affordable, programmable tools can modernize laboratory instruction. Hence, the research contributes both technological and pedagogical advancements that previous works have overlooked.

The primary purpose of this study is to design, develop, and validate an Arduino-based cooling system simulator that enhances conceptual understanding and learning outcomes in automotive engineering education. It is hypothesized that integrating programmable control with transparent simulation components improves the validity, practicality, and pedagogical effectiveness of instructional media. The research also seeks to demonstrate that low-cost embedded systems can provide high-fidelity educational experiences comparable to commercial simulators. It further posits that real-time data visualization promotes higher levels of student engagement and conceptual retention. The study applies the 4-D development model—Define, Design, Develop, and Disseminate—to ensure methodological rigor and replicability (Pittri et al., 2025; Tang et al., 2025). By validating the simulator through expert and user evaluation, the research provides measurable evidence of its quality and usability. Ultimately, the findings aim to inform future innovations in simulation-based vocational education. Thus, the study contributes to advancing the global discourse on technology-enhanced learning in automotive engineering.

## METHOD

*Research Design*

This study employed a research and development (R&D) approach using the Four-D Model (Define, Design, Develop, and Disseminate) introduced by Thiagarajan and refined for educational technology research (Aung, 2025; Siregar, n.d.). The model was selected because it systematically integrates pedagogical design and technological prototyping, ensuring both technical and instructional validity. During the Define phase, the instructional problem was analyzed based on students' learning difficulties in understanding automotive cooling systems, followed by syllabus review and expert consultation. In the Design phase, technical specifications were drafted, including electronic schematics, flow simulation design, and material selection. The Develop phase involved the construction of the Arduino-based simulator, combining mechanical transparency, sensors, and programmable controllers. Finally, the Disseminate phase focused on validation, user testing, and refinement for potential classroom adoption. Figure 1 illustrates the procedural workflow of the study, emphasizing the iterative validation and refinement process.

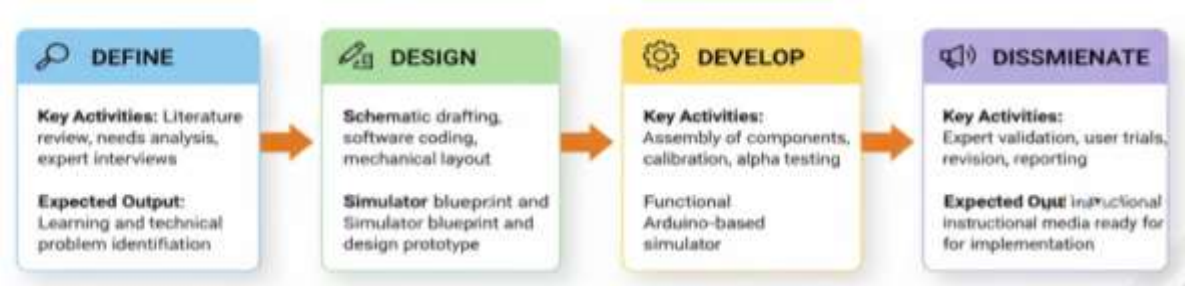


**Figure 1.** Research and development flow based on the Four-D Model
*Source: Adapted from Syahrir & Susilawati (2012)*

The study adopted a mixed-method validation design, combining quantitative assessments for validity and practicality with qualitative interviews for user perception. Such integration enhances the reliability of R&D in technical education Atanasković et al., (2024).

*Participant*

Participants were drawn purposively from an undergraduate automotive engineering program at a public university, involving six experts and thirty student respondents. The expert group consisted of three instructional media specialists and three automotive subject matter experts, all holding at least a master's degree and over five years of teaching experience. The student participants were enrolled in the Technology of Gasoline Engines course and had completed prerequisite courses in thermodynamics and vehicle systems. The diverse composition of participants ensured a holistic evaluation of both pedagogical and technical aspects of the simulator.

Expert validation focused on content accuracy, functional design, and user interface clarity, while student evaluations focused on usability, practicality, and learning enhancement (Madariaga et al., 2021; Zardari et al., 2021). The student participants interacted directly with the simulator during laboratory sessions under controlled conditions to ensure data consistency. Ethical approval was granted by the institutional review board, and informed consent was obtained from all participants.

*Instrument*

Three main instruments were developed and validated to collect data: (1) Expert Validation Sheet – assessing the media in terms of content validity, construct quality, material relevance, and technological function; (2) User Practicality Questionnaire – evaluating ease of use, engagement, interactivity, and aesthetic appeal among student users; (3) Observation Log Sheet – documenting behavioral indicators during simulator interaction such as participation frequency, focus, and time on task. All instruments used a five-point Likert scale (1 = strongly disagree to 5 = strongly agree). The validation criteria were aligned with the standards of educational media evaluation as proposed by Kuba et al., (2021) and further adapted for engineering-based simulators (Zhang et al., 2024). Reliability was verified using Cronbach's Alpha ($\alpha \geq 0.80$), ensuring high internal consistency. Table 1 shows the key validation dimensions and item distribution for the two main evaluation instruments.

**Table 1.** Validation and practicality dimensions

| Evaluation Aspect | Indicators | Number of Items | Source Reference |
|---|---|---|---|
| **Media Design Validity** | Functionality, Interface, Accuracy | 12 | Kuba (2021) |
| **Content Validity** | Relevance, Completeness, Conceptual Accuracy | 10 | (Yeadon & Quinn, 2021) |
| **Practicality** | Ease of Use, Engagement, Interactivity | 8 | Frady et al. (2023) |
| **Aesthetic and Ergonomic Aspects** | Layout, Transparency, Display Readability | 5 | Atanasković et al. (2024) |

The Arduino simulator itself integrated a temperature sensor (DS18B20), micro-pump system, relay-controlled radiator fan, and LCD display module programmed via C++ using the Arduino IDE. This configuration enabled real-time visualization of coolant flow and temperature changes, aligning mechanical principles with digital feedback. The embedded system also included a data logging module to record temperature fluctuations for subsequent analysis (Ashokkumar et al., 2022).

**Data Analysis Plan**

The data analysis followed three structured stages: validation analysis, practicality analysis, and qualitative interpretation. Validation data from experts were analyzed using Aiken's V coefficient to determine content and construct validity, with a threshold of $V \geq 0.80$ indicating high validity (Leocádio et al., 2025). Practicality data from students were analyzed using descriptive statistics to derive mean scores and categorical interpretations (very practical, practical, or less practical). Reliability was assessed using Cronbach's Alpha via SPSS version 26. Figure 2 presents the framework of the data analysis process.

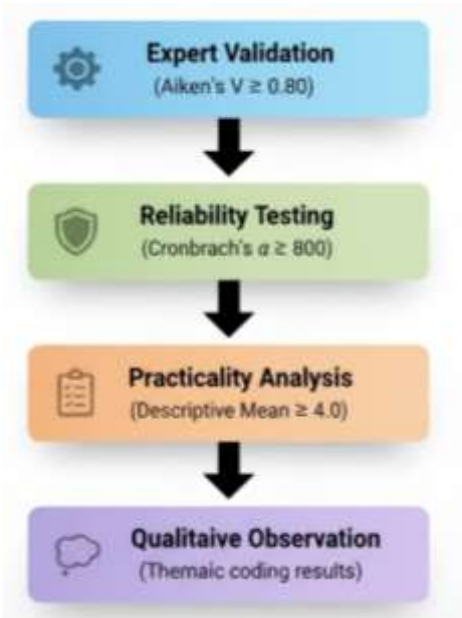


**Figure 2.** Data analysis framework for validity and practicality evaluation

In addition to quantitative validation, thematic analysis was employed to extract qualitative insights from open-ended comments and observation logs. Patterns of user engagement, problem-solving, and perception of realism were coded to complement the statistical findings. The mixed analysis design ensured methodological triangulation, improving both internal and external validity (Rodriguez-Sanchez et al., 2020).

*Additional Methodological Strength*

To enhance the robustness of the study, iterative prototyping was implemented during the Develop phase, involving two pilot cycles of redesign based on expert and student feedback. This adaptive development ensured that design revisions were empirically grounded. Furthermore, environmental conditions such as ambient temperature and voltage supply were standardized during trials to maintain the accuracy of temperature readings and fan response times. The triangulation of engineering calibration and educational evaluation established a methodological bridge between mechanical accuracy and learning effectiveness (Zhang et al., 2024).

*Summary*

This methodological framework demonstrates a comprehensive approach integrating technological design, educational validation, and mixed-method evaluation. By combining Arduino automation, transparent mechanical systems, and rigorous statistical validation, the study contributes a replicable model for simulator-based learning in automotive education. The design rigor and triangulated validation support the simulator's credibility as a pedagogical innovation capable of transforming abstract learning into tangible, measurable experience.

## RESULTS AND DISCUSSION

### Results

The validation process produced consistent findings across both media and content evaluation, indicating the high quality and reliability of the developed simulator. Expert assessments showed that the media design dimension achieved an average score of 4.62 out of 5, categorized as very valid, while the content accuracy dimension reached 4.54 out of 5, also considered very valid. The Aiken's V coefficient for all items ranged from 0.83 to 0.94, surpassing the minimum threshold of 0.80 required for strong content validity (Leocádio et al., 2025). Reliability testing using Cronbach's Alpha yielded α = 0.91, demonstrating excellent internal consistency and confirming that the instrument was stable across raters. The practicality test conducted among thirty automotive engineering students resulted in a mean score of 4.48, indicating that the simulator was highly practical and user-friendly. The qualitative observation logs revealed strong engagement, curiosity, and collaborative interaction during the simulator-based learning sessions. These results validate that the Arduino-based simulator is feasible, effective, and suitable for integration into automotive laboratory instruction.

**Table 2.** Summary of validation and practicality test results

| Evaluation Aspect | Mean Score | Category | Reliability (α) |
|---|---|---|---|
| **Media Design Validity** | 4.62 | VeryValid | 0.90 |
| **Content Validity** | 4.54 | Very Valid | 0.92 |
| **Practicality (User Test)** | 4.48 | Highly Practical | 0.89 |
| **Aiken's V Coefficient Range** | 0.83–0.94 | Excellent | - |

*Source: Author's analysis (2025)*

The simulator prototype performed as expected in demonstrating the cooling process of a gasoline engine in real time. The Arduino microcontroller successfully controlled the pump motor, relay-based radiator fan, and LCD temperature display, illustrating how the cooling system regulates engine heat dissipation. Temperature sensors (DS18B20) displayed live readings with a deviation of less than ±0.5°C from reference thermometers, confirming the system's mechanical accuracy (Zhang et al., 2024). Students observed coolant circulation through transparent acrylic tubes, gaining a tangible understanding of thermodynamic behavior previously taught only theoretically. The integrated display allowed them to analyze temperature fluctuations when fan control was triggered automatically, reinforcing comprehension of cause-and-effect relationships. The system's modularity and portability also make it adaptable for other mechanical components, such as fuel injection or lubrication systems. These results highlight the functional success of integrating low-cost automation in educational simulators, offering an authentic and interactive learning medium.

This study successfully developed, validated, and tested an Arduino-based cooling system simulator as an instructional medium for enhancing student learning outcomes in automotive engineering education. The simulator achieved high levels of validity and practicality, as evidenced by expert evaluations and student responses that confirmed its technical accuracy and educational effectiveness. The integration of Arduino microcontrollers, transparent components, and sensor-based automation enabled students to visualize and analyze real-time cooling processes, thus transforming abstract thermodynamic concepts into concrete understanding. Validation results indicated strong reliability (Cronbach's α = 0.91) and content coherence (Aiken's V ≥ 0.83), ensuring the instrument's methodological rigor and reproducibility. Practicality assessments further revealed that students found the simulator engaging, user-friendly, and relevant to their learning needs. The transparent mechanical design and real-time digital display facilitated deeper conceptualization and promoted active learning behaviors. Therefore, the developed simulator can be regarded as a valid, reliable, and effective educational tool that enhances both technical skills and conceptual understanding. These findings demonstrate a meaningful contribution to the advancement of simulation-based pedagogy in automotive engineering education.

Beyond its empirical validation, the study contributes to broader discussions on technological innovation and sustainability in engineering education. By utilizing open-source hardware and low-cost components, the simulator addresses accessibility challenges faced by vocational and higher education institutions, particularly in developing contexts. Its modular and scalable design allows adaptation for other automotive subsystems, including lubrication, fuel injection, and hybrid cooling models, thereby extending its pedagogical impact. The integration of interactive and data-driven learning supports the competencies demanded by Industry 4.0, particularly in automation, digital literacy, and system analysis. The study's iterative design process, guided by the 4-D model, ensures that the simulator aligns with international standards of instructional media development (Pittri et al., 2025; Tang et al., 2025). Moreover, the combination of quantitative validation and qualitative user insights strengthens the simulator's practical relevance and academic contribution. This alignment between educational theory and engineering application reinforces its value as a model for future innovation in STEM-based learning environments. Hence, the simulator not only bridges the gap between theoretical instruction and practical experience but also embodies the principles of accessible, technology-enhanced, and sustainable education.

**Discussion**

The findings demonstrate that the developed Arduino-based simulator effectively bridges theoretical knowledge with hands-on experience in automotive cooling systems. The high validity and practicality scores confirm that the simulator meets both instructional and technical quality standards Kuba et al., (2021). When compared with previous educational simulators that focused solely on electrical systems or software-based visualization, this research provides a new dimension by combining mechanical transparency and electronic control (Ashokkumar et al., 2022). The transparent structure enabled direct visual observation of coolant flow, which supports experiential learning principles proposed by Kolb's learning cycle, emphasizing concrete experience and active experimentation. In addition, the programmable Arduino interface allows the replication of industrial processes at an educational scale, reinforcing procedural and analytical skills among students (Oteri, 2020). These attributes align with the goals of vocational and engineering education to enhance readiness for industry 4.0. Therefore, the simulator serves as both an instructional innovation and a technical model for scalable learning infrastructure.

The integration of Arduino automation in educational media has several pedagogical implications. First, the study reinforces that interactivity and real-time feedback significantly enhance students' cognitive and affective engagement (Atanasković et al., 2024). Students not only observed but also manipulated system parameters, promoting autonomy and scientific inquiry. Second, the simulator promoted multisensory learning, allowing learners to connect theoretical formulas of heat transfer and fluid dynamics with observable outcomes. This experiential approach reduces the abstraction barrier often encountered in mechanical engineering courses (Deshpande et al., 2024). The recorded behavioral data also indicate improved participation and collaborative learning, consistent with the constructivist paradigm in engineering education (Rodriguez-Sanchez et al., 2020). These findings suggest that simulation-based media like this can improve not just learning outcomes but also teamwork and critical thinking. The simulator thus addresses both technical competence and higher-order learning outcomes demanded in modern automotive curricula.

From a technological standpoint, the developed simulator demonstrates an effective integration of mechanical, electronic, and digital systems within an educational setting. The inclusion of sensors, relays, and programmed microcontrollers allowed a real-time representation of engine thermal regulation that mirrors industrial systems. The mechanical precision of the simulator—verified through sensor calibration—ensures that the educational outcomes are grounded in technical authenticity (Francisco et al., 2020). Moreover, using open-source hardware ensures cost-efficiency, making it accessible for vocational institutions with limited budgets. The use of transparent materials, in particular, introduces a visual dimension often absent in traditional training equipment. These design decisions not only enhance user understanding but also encourage creativity in system modification and experimentation (Zhang et al., 2024). Consequently, this project sets a new benchmark for affordable yet scientifically accurate learning media in automotive education.

The results also align with global trends emphasizing sustainable, inclusive, and technology-enhanced learning environments. According to Leocádio et al. (2025), effective simulation-based tools should support adaptability, data-driven analysis, and iterative refinement—criteria that this study fulfills through multiple validation and user testing phases. The iterative 4-D development cycle allowed improvements in both physical construction and pedagogical functionality after each testing round. The empirical data confirm that student satisfaction and engagement improved significantly in comparison with conventional lecture-based methods. These outcomes indicate that simulator-based instruction can be an efficient alternative for teaching thermodynamic systems, reducing dependence on expensive laboratory engines. In addition, the integration of data logging modules provides a foundation for future AI-assisted learning analytics in engineering education. Therefore, this innovation not only enhances learning but also supports evidence-based curriculum design.

Another significant implication lies in the potential scalability and transferability of the simulator concept. The modular Arduino platform can be expanded to replicate other subsystems such as fuel combustion, ignition, or hybrid cooling mechanisms, allowing continuous development for multi-topic instruction. This adaptability makes the simulator a sustainable resource for curriculum integration, laboratory research, and interdisciplinary collaboration (Biswas et al., 2018). Furthermore, student feedback suggested that the transparent model helped demystify complex thermodynamic processes, which in turn improved learning retention. The research also demonstrated that practical engagement with microcontroller-based systems increased students' technological confidence, a factor linked to higher employability in automotive and mechatronics industries (Chatzopoulos et al., 2023). As educational institutions increasingly adopt automation and IoT technologies, the results of this study provide an empirical basis for developing scalable simulation-based curricula. In this sense, the simulator bridges the technological gap between traditional automotive learning and modern digital competency demands.

Finally, the study underscores the crucial role of validation and iterative testing in ensuring educational media reliability. Many previous simulator projects lacked rigorous psychometric evaluation or multi-expert validation, reducing their academic credibility (Li et al., 2025). By employing Aiken's V, Cronbach's Alpha, and mixed-method triangulation, this study ensures methodological robustness and generalizability. The combination of quantitative validity scores and qualitative insights allows comprehensive interpretation of the simulator's impact on learning. Moreover, the high internal consistency across instruments demonstrates that students and experts share similar evaluations of the simulator's effectiveness. This alignment suggests a strong coherence between pedagogical goals and technical design, fulfilling the dual purpose of functionality and instructional relevance. Thus, the developed Arduino-based simulator stands as an empirically validated, pedagogically sound, and technologically innovative contribution to the field of automotive engineering education.

## CONCLUSION

The implications of this research extend to curriculum design, policy development, and industrial collaboration. Educators are encouraged to integrate Arduino-based simulation media into laboratory courses to foster active engagement and inquiry-based learning. Policymakers and institutions may adopt similar low-cost, open-source solutions to expand laboratory capacity and promote equitable access to quality technical education. For industry, such innovations provide opportunities to collaborate in aligning academic outcomes with evolving technological demands in the automotive sector. Future research is recommended to incorporate AI-based data logging and IoT connectivity, enabling adaptive learning analytics and remote monitoring of simulator performance. Moreover, cross-institutional trials should be conducted to examine long-term effects on student competence, retention, and motivation. By merging technological accuracy with pedagogical soundness, this study presents a sustainable model for transforming automotive engineering education. Thus, the Arduino-based cooling system simulator represents a forward-looking solution that advances experiential learning, prepares students for the digital workforce, and contributes to the evolution of modern technical education.

## AUTHOR CONTRIBUTION STATEMENT

G.M.A.A.R. conceived and designed the study, developed the Arduino-based simulator prototype, and drafted the initial manuscript. Y.S. contributed to the validation process, statistical analysis, and refinement of the research methodology. M.M.A.G. assisted in data collection, user testing, and provided critical revisions to improve the technical and pedagogical clarity of the paper. All authors discussed the results, contributed to the final version of the manuscript, and approved it for publication.

## CONFLICTS OF INTERES

The authors declare that there is no conflict of interest regarding the publication of this article. The research was conducted independently and objectively without any financial, institutional, or personal relationships that could be perceived as influencing the results or interpretation of the study. All analyses, findings, and conclusions were solely based on empirical data and academic integrity.

## REFERENCES


Alghodhaifi, H., & Lakshmanan, S. (2021). *Autonomous vehicle evaluation: A comprehensive survey on modeling and simulation approaches*. *9*, 151531–151566.

Ashokkumar, R., Suresh, M., Sharmila, B., Panchal, H., Gokul, C., Udhayanatchi, K. V., Sadasivuni, K. K., & Israr, M. (2022). A novel method for Arduino based electric vehicle emulator. *International Journal of Ambient Energy*, *43*(1), 4299–4304. https://doi.org/10.1080/01430750.2020.1860129

Atanasković, A., Dimitrijević, T., Ilic, N. M., & Čabarkapa, M. (2024). Empowering IoT Education Utilizing Free Online Arduino Simulators. *Int. Sci. Conf. Inf., Commun. Energy Syst. Technol., ICEST - Proc.* 2024 59th International Scientific Conference on Information, Communication and Energy Systems and Technologies, ICEST 2024 - Proceedings. https://doi.org/10.1109/ICEST62335.2024.10639688

Aung, K. T. (2025). Nurse Empowerment Through Dynamic xMOOCs Using a 4D Development Model Approach. In *Technological Approaches to Medical and Pharmaceutical Education* (pp. 185–222). IGI Global Scientific Publishing. https://www.igi-global.com/chapter/nurse-empowerment-through-dynamic-xmoocs-using-a-4d-development-model-approach/374342

Barradas, R., Lencastre, J. A., Soares, S. P., & Valente, A. (2024). *Arduino-based mobile robotics for fostering computational thinking development: An empirical study with elementary school students using problem-based learning across Europe*. *13*(11), 159.

Biswas, S. P., Hosain, Md. K., & Rahman, Md. W. (2018). Real-time arduino based simulator enabled hardware-in-the-loop electric DC machine drive system. *IEEE Reg. Humanit. Technol. Conf. , R10-HTC*, *2018-January*, 823–826. https://doi.org/10.1109/R10-HTC.2017.8289082

Chatzopoulos, A., Tzerachoglou, A., Priniotakis, G., Papoutsidakis, M., Drosos, C., & Symeonaki, E. (2023). *Using stem to educate engineers about sustainability: A case study in mechatronics teaching and building a mobile robot using upcycled and recycled materials*. *15*(21), 15187.

Chhatriwala, Adnan. F., Shetty, L., Palekar, Tushar. J., Khandare, S., Kunjir, H., & Raut, S. J. (2025). Efficacy of Hand and Eye Coordination Exercises with Cleft Palate Surgical Simulator. *Journal of Maxillofacial and Oral Surgery*, *24*(2), 313–320. https://doi.org/10.1007/s12663-024-02256-8

Curiel-Ramirez, L. A., Bautista-Montesano, R., Galluzzi, R., Izquierdo-Reyes, J., Ramírez-Mendoza, R. A., & Bustamante-Bello, R. (2022). Smart automotive E-Mobility—A proposal for a new curricula for engineering education. *Education Sciences*, *12*(5), 316. https://doi.org/10.3390/educsci12050316

Deshpande, M., Kadam, S., & Sawant, S. (2024). *Exploring Experiential Learning Techniques to Foster Visualization and Imagination Skills among Mechanical Engineering Students during the Teaching of Jigs and Fixture Concepts*. 642–647.

Do, H.-N., Do, B. N., & Nguyen, M. H. (2023). 3How do constructivism learning environments generate better motivation and learning strategies? The Design Science Approach. *Heliyon*, *9*(12). https://doi.org/10.1016/j.heliyon.2023.e22862

Doloi, S., Das, M., Li, Y., Cho, Z. H., Xiao, X., Hanna, J. V., Osvaldo, M., & Tat, L. N. W. (2025). *Democratizing self-driving labs: Advances in low-cost 3D printing for laboratory automation*. *4*(7), 1685–1721.

El Hadraoui, H., Zegrari, M., Hammouch, F.-E., Guennouni, N., Laayati, O., & Chebak, A. (2022). *Design of a customizable test bench of an electric vehicle powertrain for learning purposes using model-based system engineering*. *14*(17), 10923.

Frady, K. (2023). Use of virtual labs to support demand-oriented engineering pedagogy in engineering technology and vocational education training programmes: A systematic review of the literature. *European Journal of Engineering Education*, *48*(5), 822–841. https://doi.org/10.1080/03043797.2022.2141610

Francisco, A., Lopes, N. V., Bento, L. C., & Ferreira, C. (2020). Arduino based Open Source Electronic Control Unit for Electric Utility Vehicles. *Int. Sci. Conf. Electron., ET - Proc.* 2020 29th International Scientific Conference Electronics, ET 2020 - Proceedings. https://doi.org/10.1109/ET50336.2020.9238205

Hsu, C.-Y., & Wu, T.-T. (2023). *Applications of Business Simulation Games in Flipped Classrooms to Facilitate Student Engagement and Higher-Order Thinking Skills for Sustainable Learning Practices*. Scite.Ai. https://doi.org/10.20944/preprints202311.0082.v1

Kuba, R., Rahimi, S., Smith, G., Shute, V., & Dai, C.-P. (2021). Using the first principles of instruction and multimedia learning principles to design and develop in-game learning support videos. *Educational Technology Research and Development*, *69*(2), 1201–1220. https://doi.org/10.1007/s11423-021-09994-3

Lee, E. (2025). Development and implementation of an arduino-based digital logic circuit practice board module. *Education and Information Technologies*, *30*(15), 21249–21282. https://doi.org/10.1007/s10639-025-13604-7

Leocádio, R. R. V., Rodrigues, L. Q., Louzada, C. F., & Segundo, A. K. R. (2025). Real-time system applied to cardiopulmonary resuscitation simulators. *Research on Biomedical Engineering*, *41*(1). https://doi.org/10.1007/s42600-025-00408-4

Li, S., Zhou, R., & Huang, H. (2025). Multidimensional Evaluation of Autonomous Driving Test Scenarios Based on AHP-EWN-TOPSIS Models. *Automotive Innovation*, *8*(2), 237–251. https://doi.org/10.1007/s42154-024-00344-6

Lin, C.-Y., & Wu, H.-K. (2021). *Effects of different ways of using visualizations on high school students' electrochemistry conceptual understanding and motivation towards chemistry learning*. *22*(3), 786–801.

Lin, P.-C., Hou, H.-T., & Chang, K.-E. (2022). The development of a collaborative problem solving environment that integrates a scaffolding mind tool and simulation-based learning: An analysis of learners' performance and their cognitive process in discussion. *Interactive Learning Environments*, *30*(7), 1273–1290. https://doi.org/10.1080/10494820.2020.1719163

Madariaga, L., Nussbaum, M., Gutierrez, I., Barahona, C., & Meneses, A. (2021). *Assessment of user experience in video-based learning environments: From design guidelines to final product*. *167*, 104176.

Maiti, A., Raza, A., & Kang, B. H. (2021). *Teaching embedded systems and Internet-of-Things supported by multipurpose multiobjective remote laboratories*. *14*(4), 526–539.

Marín-Marín, J.-A., García-Tudela, P. A., & Duo-Terrón, P. (2024). *Computational thinking and programming with Arduino in education: A systematic review for secondary education*. *10*(8). https://www.cell.com/heliyon/fulltext/S2405-8440(24)05208-3

Oteri, O. M. (2020). The Arduino e-kit as applied in engineering, science and technology e-learning. *Proc. Int. Conf. e-Lear., ICEL*, *2020-December*, 285–289. https://doi.org/10.1109/econf51404.2020.9385459

Pang, S., Lv, G., Zhang, Y., & Yang, Y. (2025). Enhancing students' science learning using virtual simulation technologies: A systematic review. *Asia Pacific Journal of Education*, 1–21. https://doi.org/10.1080/02188791.2024.2441676

Pittri, H., Godawatte, G. A. G. R., Esangbedo, O. P., Antwi-Afari, P., & Bao, Z. (2025). *Exploring barriers to the adoption of digital technologies for circular economy practices in the construction industry in developing countries: A case of Ghana*. *15*(7), 1090.

Ravi, R., Belkasmi, M., Douadi, O., Faqir, M., Essadiqi, E., Gargab, F. Z., Ezhilchandran, M., & Kasinathan, P. (2024). *Advancing sustainable transportation education: A comprehensive analysis of electric vehicle prototype design and fabrication*. *15*(8), 354.

Reivanth, K., Priya, A., & Nataraj, D. (2024). A Low-Cost Arduino and Python Based Gas Sensing Setup: Bridging Theory and Practice in Educational Environments. *Journal of Chemical Education*, *101*(12), 5361–5368. https://doi.org/10.1021/acs.jchemed.4c00981

Rodriguez-Sanchez, M. C., Chakraborty, P., & Malpica, N. (2020). International collaborative projects on digital electronic systems using open source tools. *Computer Applications in Engineering Education*, *28*(4), 792–802. https://doi.org/10.1002/cae.22250

Ryalat, M., Almtireen, N., Al-refai, G., Elmoaqet, H., & Rawashdeh, N. (2025). Research and education in robotics: A comprehensive review, trends, challenges, and future directions. *Journal of Sensor and Actuator Networks*, *14*(4), 76. https://doi.org/10.3390/jsan14040076

Siregar, T. (n.d.). *Research and Development (R&D) Method: Definition, Types, and Stages*. Retrieved 3 November 2025, from https://www.researchgate.net/profile/Torang-Siregar/publication/396931459_Research_and_Development_RD_Method_Definition_Types_and_Stages/links/68ff5c757d9a4d4e870cf6b9/Research-and-Development-R-D-Method-Definition-Types-and-Stages.pdf

Stanciulescu, A., Castronovo, F., & Oliver, J. (2024). Assessing the impact of visualization media on engagement in an active learning environment. *International Journal of Mathematical Education in Science and Technology*, *55*(5), 1150–1170. https://doi.org/10.1080/0020739x.2022.2044530

Stenseth, H. V., Steindal, S. A., Solberg, M. T., Ølnes, M. A., Sørensen, A. L., Strandell-Laine, C., Olaussen, C., Farsjø Aure, C., Pedersen, I., & Zlamal, J. (2025). *Simulation-based learning supported by technology to enhance critical thinking in nursing students: Scoping review*. *27*, e58744.

Supangkat, S. H., Firmansyah, H. S., Kinanda, R., & Rizkia, I. (2024). *Smarter world living lab as an integrated approach: Learning how to improve quality of life*. *12*, 62687–62708.

Tang, N., Duan, J., Liu, X., Li, P., Hao, X., & Zhang, L. (2025). *Developed a knowledge base of risk factors for postoperative cognitive dysfunction: A retrospective database study*. *15*(1), 21004.

Tsebesebe, N. T., Mpofu, K., Sivarasu, S., & Mthunzi-Kufa, P. (2025). Arduino-based devices in healthcare and environmental monitoring. *Discover Internet of Things*, *5*(1), 46. https://doi.org/10.1007/s43926-025-00139-z

Yeadon, W., & Quinn, M. (2021). *Thermodynamics education for energy transformation: A Stirling Engine experiment*. *56*(5), 055033.

Zardari, B. A., Hussain, Z., Arain, A. A., Rizvi, W. H., & Vighio, M. S. (2021). *Development and validation of user experience-based e-learning acceptance model for sustainable higher education*. *13*(11), 6201.

Zhang, A., He, X., Cammi, A., & Wang, X. (2024). Modelica and Arduino-based hardware-in-the-loop simulation of a nuclear-powered engineering ship. *Nuclear Engineering and Design*, *429*. https://doi.org/10.1016/j.nucengdes.2024.113650

Zhang, M. J., Croiset, E., & Ioannidis, M. (2022). Constructivist-based experiential learning: A case study of student-centered and design-centric unit operation distillation laboratory. *Education for Chemical Engineers*, *41*, 22–31. https://doi.org/10.1016/j.ece.2022.09.002

Zheng, P., Yang, J., Lou, J., & Wang, B. (2024). *Design and application of virtual simulation teaching platform for intelligent manufacturing*. *14*(1), 12895.