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Developing marker-based augmented reality for Arduino components using MongoDB and Flask

Ega Mardoyo[1*], Sarosa Castrena Abadi[2], Ridwan[3], Siti Aminah[4]

[1,4] Industrial Informatics Engineering Technology, Department of Manufacturing Automation Engineering and Mechatronics, Politeknik Manufaktur Bandung, **Indonesia**
[2] Automation Engineering Technology, Department of Manufacturing Automation Engineering and Mechatronics, Politeknik Manufaktur Bandung, **Indonesia**
[3] Mechatronics Engineering Technology, Department of Manufacturing Automation Engineering and Mechatronics, Politeknik Manufaktur Bandung, **Indonesia**

[*]Corresponding author: ega@polman-bandung.ac.id

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Abstract: Students can find it difficult to understand the functions and operation of Arduino Starter Kit components when learning materials rely mainly on two-dimensional representations. Augmented reality (AR) can help address this challenge by providing interactive, real-time visualizations of three-dimensional (3D) objects. This study developed an AR-based learning application using Unity and Vuforia, with a Flask backend and MongoDB, a document-oriented, non-relational database commonly described as NoSQL ("Not Only SQL," where SQL stands for "Structured Query Language"). The application uses marker-based tracking to recognize target objects and display the corresponding 3D component models. It retrieves related information from MongoDB through an application programming interface (API) using key-based lookups. The system integrates data between the web dashboard and AR application in real time so that displayed information reflects the database's key–value structure. Functional testing showed that the application could display interactive 3D models based on recognized targets and present component information dynamically. The system offers an interactive resource for helping students learn fundamental microcontroller concepts; its impact on learning outcomes has not yet been evaluated.

Keywords: Augmented reality; Arduino; marker-based tracking; NoSQL; Unity

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1. Introduction

The rapid development of Internet of Things (IoT) technologies and embedded systems has increased the use of microcontroller boards, including the ATmega328P-based Arduino Uno R3, in engineering education (M. Wu & Chen, 2024; Z. Wu et al., 2020). Understanding the board's physical structure, pin layout, and component functions is a fundamental competency for students (Boomgaard et al., 2022; Kunkel et al., 2025). However, conventional instruction can be challenging because technical documentation and datasheets are often extensive and complex. For example, the ATmega328P datasheet spans 294 pages (Hafiz et al., 2025; Lucas Bonilla et al., 2025).

Limited school budgets for physical laboratory equipment can further constrain practical learning opportunities (Reyes et al., 2024). Switching between schematic materials and physical boards may also increase students' cognitive load and reduce learning efficiency (Bautista et al., 2023). Flask is a lightweight, flexible Python web framework for developing interactive web interfaces and Representational State Transfer (REST)-based application programming interface (API) services (Kocatekin et al., 2026; Oktaviano et al., 2026; ScholarHub et al., 2024; Zhang, 2026).

Marker-based augmented reality (AR) provides an interactive learning medium by overlaying three-dimensional (3D) virtual objects onto the physical environment in real time (Pane & Darnila, 2025; Pratama & Sukirman, 2023). Research has shown that AR can support student engagement, motivation, and understanding through interactive 3D visualizations (Tarng et al., 2024; Zekeik et al., 2025). It also enables users to examine objects in greater detail and in context, which can help them understand complex concepts (Hajirasouli et al., 2022; Mendoza-Ramírez et al., 2023; Reipschlager et al., 2021).

Fiducial markers, including ArUco markers, Quick Response (QR) codes, and image targets, can be detected using computer vision libraries such as the Open Source Computer Vision Library (OpenCV). These libraries support marker detection, feature extraction, and 3D pose estimation (Garrido-Jurado et al., 2026; Ribeiro Neto et al., 2026). In educational settings, AR has been associated with greater student motivation, improved spatial understanding, and more interaction; it may also reduce reliance on physical equipment (Mansour et al., 2025; Rohendi et al., 2025).

Building on studies that used AR to visualize circuits and hardware, this study develops a marker-based AR application that recognizes Arduino Uno R3 components and integrates with Flask and MongoDB (Altmeyer et al., 2020; Asham et al., 2023). The application is intended to make hardware components easier to visualize, address limitations in access to physical laboratory equipment, and provide instructors with a responsive way to manage learning materials.

2. Materials and Methods

This study developed an augmented reality (AR) application that integrates MongoDB, a document-oriented non-relational database, with the Flask web framework. Development followed the Waterfall model (Monte Pegado et al., 2025; Ruiz-Zafra et al., 2024). The model consists of requirements analysis, system design, implementation, testing, deployment, and maintenance phases (Systems Design and Life Cycle, 2008).

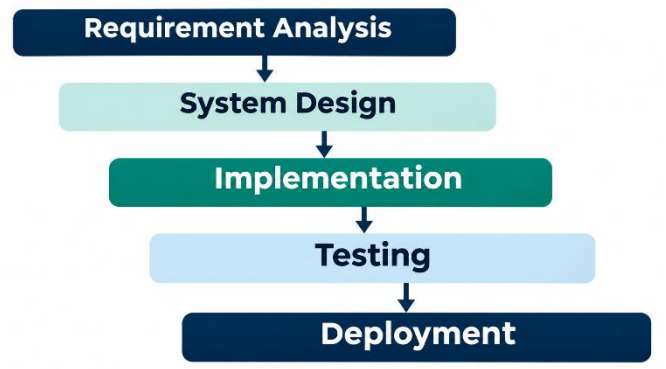


Figure 1. Waterfall Methods

2. 1 Requirements Analysis Phase

The requirements analysis phase established the system's objectives, scope, and specifications. The project addressed a common learning challenge: students may struggle to understand the functions and operation of Arduino components when learning materials rely primarily on two-dimensional representations.

System requirements were assessed from both user and technical perspectives. For users, the application needed to provide an interactive way to view Arduino Uno components and ultrasonic sensors while presenting clear, accessible information. Technically, it needed to integrate web services, a database, and the AR application in real time. It also needed to retrieve database records by key and display information

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corresponding to objects recognized by the camera. These requirements align with prior research suggesting that visual and interactive AR experiences can support understanding of complex concepts.

2. 2 System Design Phase

This phase defined the application workflow and its two main user roles: administrator and user. The administrator enters and manages component data, while users interact with the application's visual output. These interactions are represented in the use case diagram.

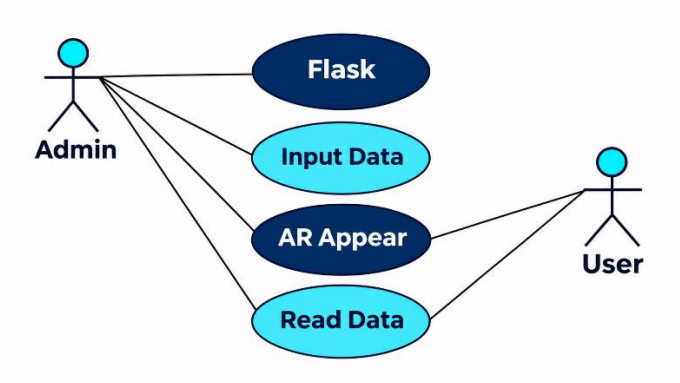


Figure 2. Use Case Diagram

The system design phase also specified the application architecture, database structure, and technical workflow. MongoDB was selected to store component data as documents and support retrieval by key. A Flask-based API connects the database to the AR application. The design also covered marker creation, camera-based object recognition, API requests for data retrieval, and the display of 3D objects with their associated information.

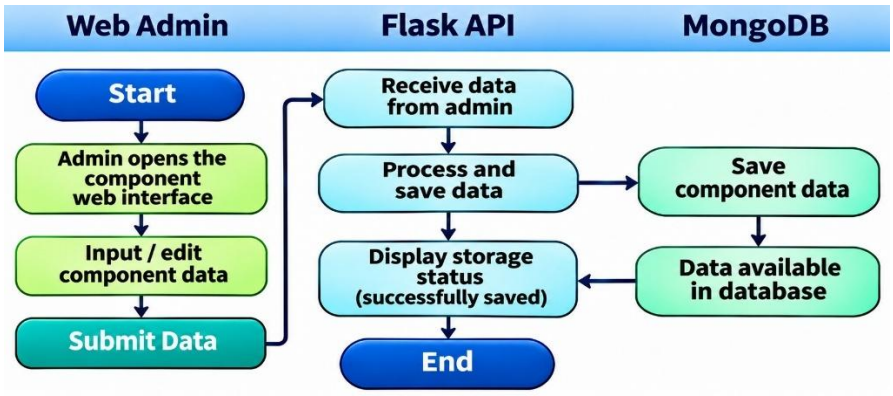


Figure 3. Administrator Workflow

Figure 3 illustrates the workflow for managing component data through the web dashboard. The process begins when the administrator accesses the web application and adds or updates component data. The submitted data is processed by the Flask API and saved to the MongoDB Atlas database. Once the data has been stored, the system displays a success notification. This process allows the information displayed in the AR application to be updated dynamically.

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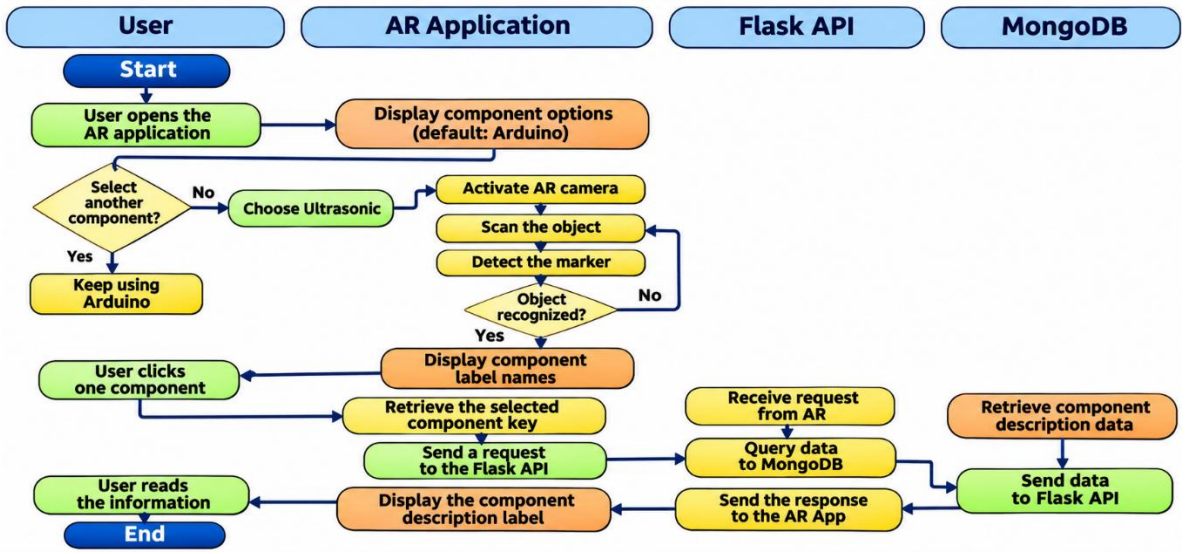


Figure 4. AR Application Usage Workflow

Figure 4 illustrates the AR application workflow during user interaction. The process begins when the user opens the application and selects a component module; Arduino is selected by default. The user can switch to the ultrasonic sensor module using the menu. The application then activates the smartphone camera to scan a physical object using Vuforia. If the object is not recognized, scanning continues. Once the object is detected, the application displays a 3D model with interactive component labels.

When a user taps a label, the application sends the associated key to the Flask API. The API uses that key to query MongoDB Atlas for the corresponding descriptive text, which is then displayed in the AR application in real time.

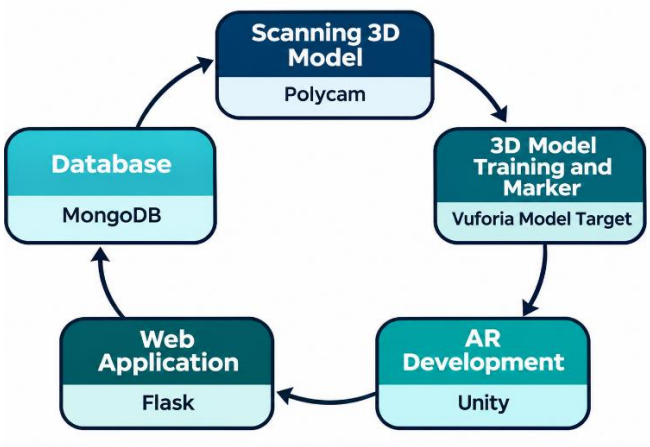


Figure 5. Technology Architecture

Figure 5 summarizes the technology architecture used to develop the application. The workflow includes scanning 3D models with Polycam, preparing 3D objects and targets with Vuforia Target Manager, developing the AR application in Unity, building the backend and web application with Python and Flask, and storing data in MongoDB.

2. 3 Implementation Phase

During implementation, the system design was translated into software. Flask provided the API services, and MongoDB stored component data as documents. An administrator dashboard supported data

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management. The client-side AR application was built with Unity and Vuforia Engine and used marker-based tracking to recognize physical targets and display information in real time. Polycam was used to create the 3D component models through scanning.

2. 4 Testing Phase

The application was evaluated through functional testing using the black-box testing method. The test scenarios and results are presented in Table 1.

Table 1. Black-Box Testing Results

No.	Module / Test Class	Test Scenario	Expected Result	Actual Result	Status
1	Web Dashboard	Accessing the admin dashboard main page.	Displays the main page with two learning module options: Arduino and Ultrasonic Sensor (Figure 6).	The main page and module choices were successfully displayed.	Valid
2	Web Dashboard	Accessing the Arduino module data management page.	Displays the description input page, including a component type selection field and a description text area (Figure 7).	The Arduino component input page functioned and displayed correctly.	Valid
3	Web Dashboard	Accessing the Ultrasonic module data management page.	Displays a dedicated description input page for Ultrasonic Sensor components (Figure 8).	The Ultrasonic component input page functioned and displayed correctly.	Valid
4	API & Database Integration	Entering or updating component data via the web dashboard.	Data is sent to the Flask API, saved in MongoDB Atlas, and updated automatically without modifying the AR application.	Data was stored successfully, and updates were applied dynamically.	Valid
5	AR Application	Using the drop-down menu on the AR camera interface.	The drop-down menu displays the available module options (Arduino/Ultrasonic) and switches the scan target (Figures 9 and 10).	The drop-down menu functioned properly for switching component modes.	Valid
6	AR Application	Scanning physical objects, such as an Arduino Uno, using a smartphone camera.	The camera detects the physical object and displays a 3D model with interactive component labels (Figure 11).	The system successfully recognized the object and displayed the 3D model with its labels.	Valid with notes
7	AR Application	Selecting an interactive component label on the 3D model, such as Digital Pins.	The application retrieves data via the Flask API and displays a real-time description panel (Figure 12).	The description appeared instantly and matched the database entry.	Valid

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2. 5 Deployment / Publication Phase

After testing, the Flask-based web application was deployed to a hosting server and made available through a public domain. As a result, the administrator dashboard and API services could be accessed online. The Unity AR project was compiled as an Android application package (APK) and installed on Android smartphones. The application connects to the centralized database through Flask and MongoDB Atlas.

3. Results and Discussion

The resulting learning application integrates the Flask API with MongoDB Atlas and has two main components: a web dashboard for administrative data management and an Android AR application for real-time 3D visualization.



Figure 6. Main Interface of the AR Dashboard

When the administrator opens the web dashboard, they can select a learning module: Arduino or Ultrasonic Sensor (Figure 6). This page serves as the starting point for managing component data.

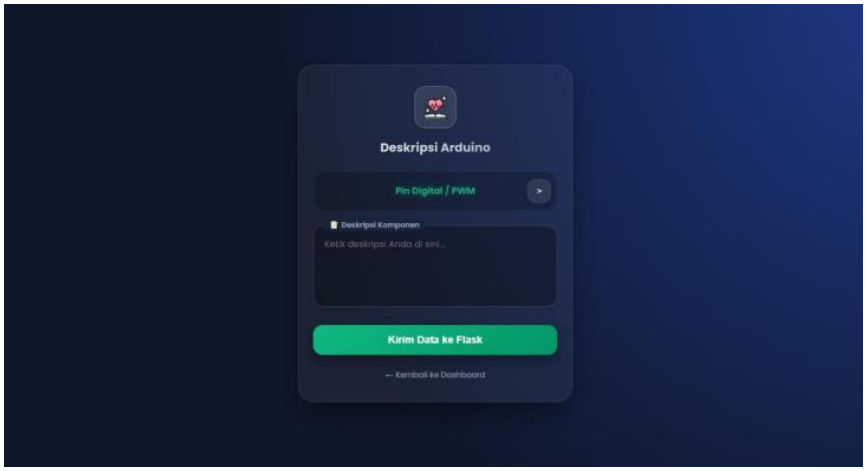


Figure 7. Description Input Page for Arduino Components

After selecting a module, the administrator is directed to the corresponding component description page. On this page, the administrator can add or update information about the selected component. Figure 7 shows the Arduino component input page, which provides a component type selector and a text area for entering descriptions.

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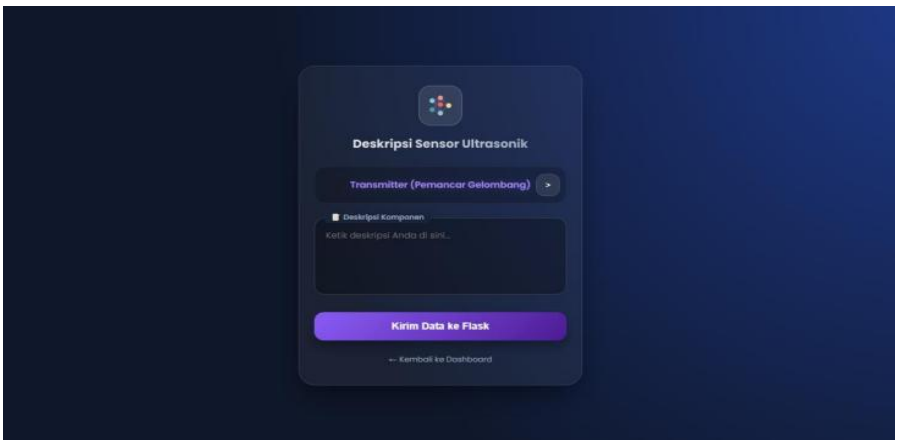


Figure 8. Description Input Page for Ultrasonic Sensor Components

A similar input page is available for Ultrasonic Sensor components. Figure 8 shows the page used to manage information about the transmitter and other component parts.

Data entered through the web dashboard is sent to the Flask API and stored in MongoDB Atlas. This process allows data to be updated without modifying the AR application. In the AR application, users can select the type of component to scan from a drop-down menu. Figure 9 shows the initial AR camera interface, with Arduino selected.



Figure 9. Initial Interface of the AR Application

Users can change the selected component to the Ultrasonic Sensor using the available menu. Figure 10 shows the component selection menu in the AR application.

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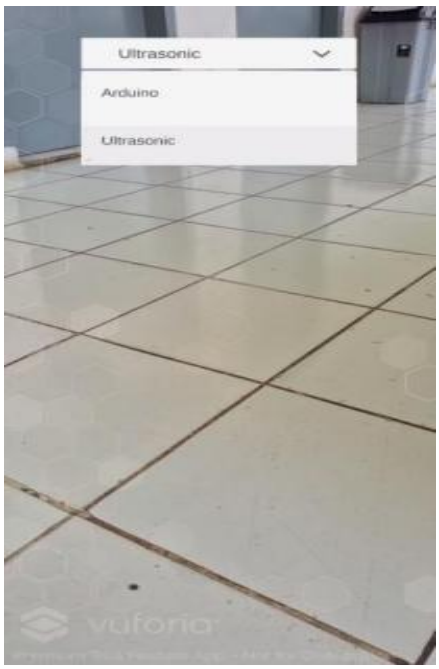


Figure 10. Drop-Down Menu for Selecting Between Arduino and Ultrasonic Sensors

After selecting a component, users can scan the physical object with the camera. Once the object is recognized, the application displays its visual model with interactive component labels. Figure 11 shows the detected Arduino Uno with labels for Digital Pins, Analog Pins, Arduino Power, and Universal Serial Bus (USB) Port.

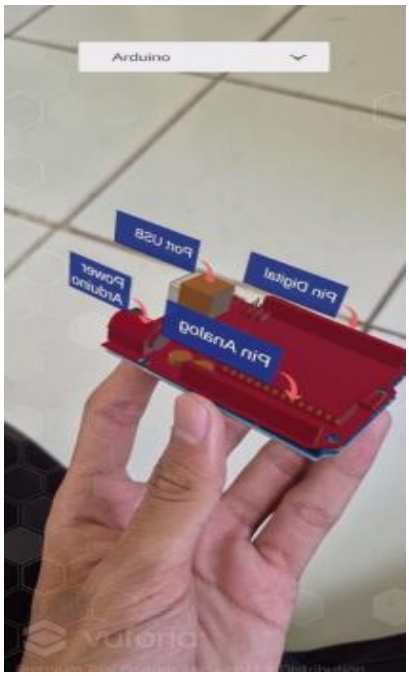


Figure 11. Arduino Object Visualization with Interactive Component Labels in the AR Application

When a user selects a component label, the application displays detailed information in a description panel. The information is retrieved from the database through the Flask API. Figure 12 shows the description for the Digital Pin component, displayed in real time.

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Figure 12. Description Information Display for Arduino Components

As shown in Figure 12, the application displays a 3D model of the Arduino component together with its descriptive information. The application's functionality was evaluated using black-box testing, and the results are summarized in Table 1.

Black-box testing showed that the tested functions met the specified requirements. These included create, read, and update (CRU) operations on the administrator dashboard, 3D-object display, and API-based data retrieval in the Android application. Integrating the Unity front end with the Flask–MongoDB back end enabled administrators to manage data through the web dashboard and display it in the AR application (Fischl et al., 2026; Han et al., 2025; Vidal-Balea et al., 2021).

One limitation was observed in Scenario 6, which tested object tracking. The result was classified as "Valid with notes" because the Arduino board needed to be positioned upright or facing upward during the initial scan. When the board was upside down or substantially tilted at the start of scanning, the Vuforia engine had difficulty initiating the 3D model projection (El Barhoumi et al., 2022).

4. Conclusion

This study developed, implemented, and evaluated an augmented reality (AR) learning application for electronics. The application recognizes Arduino Uno and ultrasonic sensor components and presents three-dimensional (3D) models with interactive labels and descriptions. It uses Flask API services and MongoDB Atlas to retrieve component information in real time. Its client–server architecture allows administrators to update learning content through a web dashboard without requiring students to reinstall or update the application. The interface was designed to be straightforward and user-friendly. However, Vuforia tracking remains sensitive to object orientation: components must be positioned upright and facing upward for reliable camera-based recognition.

Further work is needed to improve the application's technical performance and educational value. The 3D models produced from Polycam scans contain minor visual imperfections and incomplete surface details; refining them with dedicated 3D-modeling software could improve their appearance and accuracy. Object detection could also be made more flexible by training Vuforia Model Targets on a wider range of object positions and viewing angles, potentially enabling recognition from multiple directions up to 360

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degrees. The application's usability should be evaluated with more students and instructors to assess user satisfaction, perceived usefulness, and its effectiveness as an interactive learning medium. Future empirical studies should also examine the application's effects on students' conceptual understanding and learning outcomes. Finally, supporting more hardware components and electronic modules, together with more comprehensive descriptions and interactive features, could broaden the application's coverage and strengthen its value as a digital learning resource for electronics education.

Author's declaration

Author Contributions

Ega Mardoyo: Conceptualization, methodology, investigation, experimentation, application development, data curation, formal analysis, validation, writing original draft, writing review and editing, visualization. **Sarosa Castrena Abadi**: Conceptualization, supervision, validation, and writing review and editing. **Ridwan**: Conceptualization, supervision, validation, and writing review and editing. **Siti Aminah**: Conceptualization, supervision, validation, and writing review and editing.

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Data availability

The raw data and other research materials are available upon request.

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Conflict of interest

The authors declare no conflicts of interest related to this study.

Ethical clearance

Not applicable

Artificial Intelligence (AI) Use Statement

In preparing this manuscript, the authors used ChatGPT (OpenAI) to improve its clarity and coherence and Grammarly to check and correct its grammar.

Publisher's and Journal's Note

The Researcher and Lecturer Society, as publisher, and the editor of the Journal of Computer-based Instructional Media declare that they have no conflict of interest regarding the publication of this article.

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