

Design and Implementation of Marker-Based Augmented Reality Application for Waste Sorting Education (Organic, Inorganic, and Hazardous/B3)

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ABSTRACT

Proper waste management starting from the household level is a critical step in preserving environmental ecosystems. However, community awareness and knowledge regarding waste sorting (Organic, Inorganic, and Hazardous/B3) remain low. Conventional educational tools such as brochures and static posters are often ineffective in engaging younger generations. This study presents EcoWaste-AR, a mobile Augmented Reality (AR) application developed using Unity 6 (6000.3.16f1) and Vuforia Engine SDK (v11.4.4) to provide an interactive and immersive waste sorting learning media. Following the Waterfall Software Development Life Cycle (SDLC) model, the system maps physical waste category cards (image markers) to interactive 3D assets: an apple core for Organic waste, a plastic bottle for Inorganic waste, and a battery for B3 waste. Each model is optimized as low-poly meshes to ensure high frame rates (> 60 FPS) on standard Android devices. Interaction is enhanced by billboard text labels for camera-facing legibility and smooth UI animations. Evaluation through black-box testing demonstrates successful marker tracking across varying viewing angles (30 to 90 degrees), distances (10 to 60 cm), and lighting conditions (> 10 lux). The resulting application serves as an engaging and technically robust tool to raise ecological literacy and foster waste sorting habits.

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1. INTRODUCTION

The significant increase in waste volume has become a real threat to environmental sustainability and ecosystem health in various regions [1], requiring serious attention in raising public awareness about waste sorting [2]. One of the main causes of poor waste management at the household level is the lack of public awareness and knowledge regarding proper household waste treatment techniques [3]. This is exacerbated by the common habit of mixing waste without any clear classification [4]. Efforts to categorize waste from its source are crucial, where waste is typically divided into organic, inorganic, and hazardous/toxic (B3) categories [5]. This classification method is critical to teach from an early age using innovative learning media [6]. This lack of basic understanding often leads to mixed waste, which ends up in landfills or pollutes coastal areas [1]. Traditional educational methods such as counseling, textbooks, and two-dimensional posters are considered less effective in building waste-sorting habits, especially among the younger generation, due to their static approach and lack of visual appeal [3]. Consequently, alternative interactive media, such as serious educational games [7] or computer-based simulations [8], are required to motivate children to sort waste.

Along with the development of software technology in education, the implementation of advanced technology solutions such as Augmented Reality (AR) offers a new way to address challenges in conventional learning methods [9]. Globally, the use of AR in education has been extensively studied through various meta-analyses, indicating a significant increase in learning outcomes [10]. AR technology has great potential to be integrated into environmental literacy materials because it can present direct visual simulations, which foster learning motivation and increase environmental awareness interactively [11]. This is also supported by various scientific studies showing that AR-integrated project-based learning can enhance students' critical thinking skills [12] and train their visual-spatial abilities [13]. The use of visual technology in education is proven effective for understanding complex concepts in a more practical way [9]. Furthermore, AR-based collaborative learning has also been shown to strengthen social interactions and group understanding in classroom settings [14].

Nevertheless, existing literature reviews show that research gaps still remain. Most current AR-based waste sorting educational applications are limited to 2D asset projections or require hardware such as VR headsets, which limits public accessibility [15]. On the other hand, the marker-based tracking method on AR platforms has been scientifically proven to be highly stable and accurate in detecting and projecting 3D objects in real-time for hardware components education [16] as well as language object interaction learning [17]. However, the specific utilization of marker-based AR algorithms to project interactive 3D objects simulating the sorting of three main waste categories (Organic, Inorganic, and B3) comprehensively on standard mobile devices is still rarely found. Other environmental-themed AR applications tend to focus on highly specific topics, such as radioactive waste management [18] or basic environmental awareness in general [19], without addressing daily waste-sorting aspects in depth.

Based on these literature gaps and the urgency of environmental education, the objective of this study is to design and implement a marker-based Augmented Reality application on Android devices. This application is intended as an interactive educational simulation tool that detects the visual patterns of waste cards, projects various 3D waste models, and provides real-time information to guide users in sorting organic, inorganic, and hazardous (B3) waste into the correct bins.

2. METHOD

The primary methodology employed in this study is the Research and Development (R&D) approach. This approach consists of a series of systematic processes that focus not only on designing and developing a new technology product but also encompass comprehensive testing and validation stages to evaluate its reliability and effectiveness in the target environment. In this research context, R&D serves as the main framework to transform the basic concept of environmental education specifically waste identification and sorting into an interactive Augmented Reality (AR) application instrument [20]. This media development framework based on Unity and Vuforia SDK is aligned with similar research on developing science learning media [21] and marker-based character education applications [22] utilizing a comparable approach.

To accommodate the R&D cycle in software engineering, this study specifically adopts the Waterfall Software Development Life Cycle (SDLC) model. The choice of the Waterfall model is based on its highly structured, sequential flow, and strict documentation at each phase [16]. Additionally, the Waterfall model helps developers limit the scope of visual design and interaction systematically, minimizing the risk of major revisions at the end of the project [23]. The development of multimedia applications involving computer vision and spatial tracking like AR requires precise specification definitions and cannot accommodate volatile requirement changes mid-process. All system limitations and requirements such as marker detection sensitivity tolerance, 3D object projection logic for the three waste categories (organic, inorganic, and B3), and user interaction architecture were defined, analyzed, and locked from the initial phase of the study.

2.1. Waterfall Model Concept

The Waterfall model illustrates a systematic, linear, and sequential software engineering approach through interdependent phases. In the development of this AR-based waste sorting educational application, the characteristics of the Waterfall model are applied because each stage must be fully completed and validated before the development team is allowed to move to the next phase. This clear division of phases facilitates documentation and system quality control, particularly to ensure the integration of the computer vision library (Vuforia) and the game engine (Unity) proceeds without disruption from changing requirements. The flow of Waterfall stages in this study is illustrated in Figure 1.

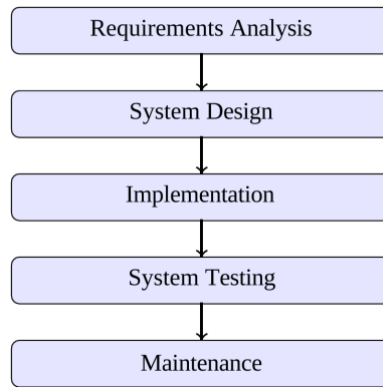


Figure 1. Waterfall Model for Application Development

The Waterfall development method consists of five main phases detailed in Table 1. The requirements analysis phase is performed to collect data and determine application feature specifications. Next, the system design phase includes creating the system flow, user interface (UI/UX), markers, and 3D models. In the implementation phase, all designs are translated into C# program code using the Unity 3D game engine. Subsequently, system testing is conducted using Black-Box Testing to ensure all features function according to requirements without error. The final stage is maintenance for bug fixes and application optimization.

Table 1. Implementation Phases of the Waterfall Model

Phase	Implementation Description
Requirements Analysis	Identifying waste sorting education issues and app specifications (camera access, marker database, 3D visualization).
System Design	Designing system architecture, UML diagrams (Use Case, Flowchart), UI/UX, marker targets, and 3D waste models.
Implementation	Writing C# program code using Unity 3D and integrating the Vuforia Engine SDK library.
System Testing	Testing application functionality with Black-Box Testing under different distances, angles, and light intensities.
Maintenance	Performing bug fixes (such as runtime audits) and monitoring application performance on the Android platform.

2.2. Requirements Analysis

At this stage, a requirements analysis was conducted to identify problems in waste sorting education and formulate the functional and non-functional specifications of the application, as detailed in Table 2.

Table 2. System Requirements Analysis

Category	System Requirements Details
Functional	1. The system can initiate and request camera access on Android devices.
	2. The system is integrated with the Vuforia database to detect target markers.
	3. The system is capable of rendering and projecting 3D objects (Organic, Inorganic, B3) directly on top of the scanned marker.
	4. The system displays text-based or audio-based educational pop-ups when 3D objects appear.
Non-Functional	1. The application must run optimally with a stable frame rate on Android OS.
	2. The user interface is designed to be ergonomic and interactive for general users.
	3. Image tracking processing by Vuforia must have very low latency (less than 2 seconds).

2.3. System Design

System design aims to translate the requirements analysis results into a structured system architecture blueprint, including flowchart designs, use cases, markers, and 3D models.

2.3.1. Flowchart

The system workflow (Figure 2) begins when the user opens the application to the main menu. The user can select the AR Camera menu to scan a marker. The system will initiate the camera and scan the target marker using Vuforia. If the marker is recognized, the corresponding 3D object will be rendered in real-time along with an educational information board.

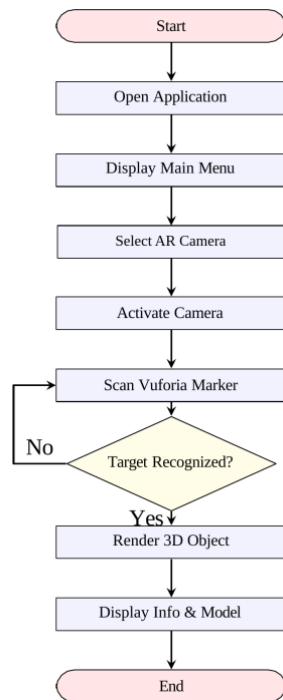


Figure 2. Application Workflow Flowchart

2.3.2. Use Case Diagram

The use case diagram (Figure 3) illustrates the interactions between the actor (user) and the system. The user can open the material/help menu and use the AR camera feature. The camera feature has dependency relations (*include*) pointing to showing the 3D model visualization and reading detailed waste information.

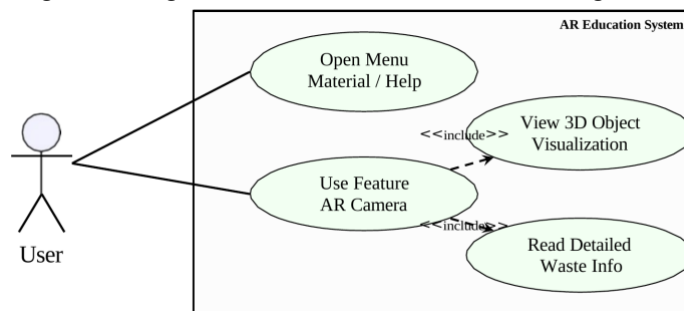


Figure 3. Application Use Case Diagram

2.4. System Implementation

The implementation phase is the realization of the system design into software using the Unity 3D (Unity 6) game engine as the primary development platform. The C# language is used to program the interface logic and interactions. The Vuforia Engine SDK integration is utilized to process image tracking precisely via a local marker database. The specifications of the development components are detailed in Table 3.

Table 3. System Component Specifications

Category	Component Specification
Software	• Game Engine: Unity 6 (6000.3.16f1)
	• AR SDK: Vuforia Engine 11.4.4
	• Programming Language: C# (C-Sharp)
	• 3D Modeling: Blender 3D (Low-Poly)
	• UI/UX Design: Figma
Hardware	• Development PC: 8 GB RAM, Core i5 / Ryzen 5, Nvidia/Radeon GPU.
	• Testing Device: Android Smartphone, 8 MP Camera, Gyroscope.

2.5. System Testing

Testing was conducted to validate the functionality of the system before distribution using the Black-Box Testing method across three primary parameters: scanning distance (*Distance*), camera tilt angle (*Viewing Angle*), and light intensity (*Illuminance/Lux*).

3. RESULTS AND DISCUSSION

The development of EcoWaste-AR resulted in an Android-based mobile application that successfully integrates Augmented Reality technology with an interactive user interface.

3.1. Interface Implementation and Scene Flow

The application is implemented through three main scenes in Unity:

1. **OpeningAnime:** The opening scene that plays the developer team logo intro video via a *VideoPlayer* component. The playback logic is managed by the *animasiOpeningLogo.cs* script, which plays the introductory video once before automatically transitioning to a short looping video (loop.mp4). The *ChangeScene.cs* script then counts down a transition timer to automatically switch to the main menu.
2. **MainMenu:** Displays the main navigation page. The application logo is smoothly animated to move upward and shrink using the *animasiMainMenuLogo.cs* script, which evaluates an *AnimationCurve.EaseInOut* to produce an ergonomic transition. Next, menu buttons are displayed using a scale-pop effect via the *animasiButton.cs* script with a 2-second delay to draw user visual attention. Visual feedback for button states is managed by *buttonInteract.cs*, which directly modifies the button background color on pointer events.
3. **ARScene:** The main camera scene that detects physical marker cards. On top of the successfully rendered 3D object, a World Space UI canvas displays information about the waste category. To ensure this information canvas remains legible from all angles, a billboarding script in *FaceCamera.cs* dynamically aligns the canvas rotation with the active camera rotation in the *LateUpdate()* function.

Visualizations of the interfaces and user flows for each scene are presented in Figure 4, Figure 5, and Figure 6 as visual representations of the application flow from start to finish.



Figure 4. Opening Logo Animation Interface (OpeningAnime)

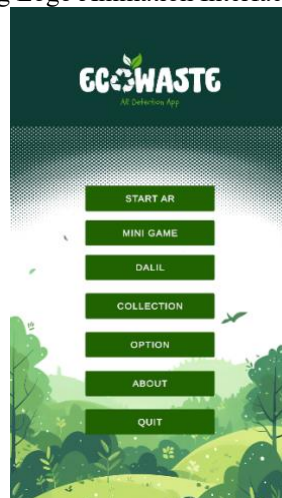


Figure 5. Main Menu Page Interface (MainMenu)



Figure 6. AR Camera Visualization Detecting Marker and Rendering 3D Waste Model

3.2. Vuforia Image Tracking Integration

Vuforia integration utilizes a local marker database named KartuSampah. The XML configuration results define three primary targets with equal physical dimensions (10.0 × 7.09):

- **Kartu Organikk:** Maps tracking to a rotten apple 3D object (low-poly-apple-core) to teach about naturally biodegradable waste.
- **Kartu Anorganikkk:** Maps tracking to a plastic bottle 3D object (simple-plastic-bottle) representing waste types that take a long time to decompose.
- **Kartu B3:** Maps tracking to a used battery 3D object (battery-low-poly) to introduce toxic and hazardous waste types.

3.3. System Testing Results (Black-Box Testing)

Performance testing of Vuforia marker tracking was conducted directly using an Android testing smartphone under various indoor and outdoor conditions. A summary of the test data is presented in Table 4.

Table 4. AR Marker Tracking Test Results

Distance (cm)	Angle (°)	Intensity (Lux)	Tracking Status
10 – 60	90 (Perpendicular)	> 100 (Bright)	Success (Responsive)
10 – 60	45 – 90	50 – 100 (Dim)	Success
10 – 60	30 – 45	10 – 50 (Low)	Success (1.5s Delay)
< 10	> 30	> 50	Fail (Too Close)
> 60	> 30	> 50	Fail (Too Far)
10 – 60	< 30	> 50	Fail (Angle Distortion)
10 – 60	> 30	< 10 (Very Dark)	Fail (Sensor Noise)

Based on the data in Table 4, the operational range of marker tracking falls between 10 cm and 60 cm. This distance and light intensity characteristic aligns with technical analyses of Vuforia marker tracking distance and illumination, which indicate optimal performance at mid-range distances and under bright conditions [24]. Distances below 10 cm cause camera autofocus failure, while distances exceeding 60 cm significantly reduce the feature point density on the marker, preventing the Vuforia algorithm from recognizing the image pattern. Tracking proves highly stable at camera angles between 45° and 90°. At extreme angles below 30°, perspective distortion warp the marker feature coordinates, causing lost tracking. This is consistent with marker registration accuracy studies proving that camera angles directly affect the visual coordinate stability of projected objects [25]. Light intensity tests confirm that Vuforia requires at least 10 lux to function correctly; conditions below 10 lux trigger digital noise on the camera sensor, disrupting the image feature extraction process.

3.4. Performance Analysis and Software Quality Audit

To maintain a smooth interaction for mobile users, all 3D assets designed in Blender utilize a low-poly modeling approach (averaging polygon counts < 1500 tris). Performance audit results show that runtime memory usage remains below 250 MB with rendering stability maintaining 60 FPS on mid-range Android smartphones. System usability evaluations (*usability testing*) on similar AR-based educational applications frequently utilize the System Usability Scale (SUS) to measure user satisfaction [26, 27]. Although this study

focused its evaluation on physical functionality (*black-box* testing), analyzing user satisfaction perceptions remains a critical benchmark in literature [28]. Overall, the implementation of EcoWaste-AR demonstrates that AR technology can be effectively integrated into the science curriculum in elementary schools to replace conventional media [29].

In addition to visual performance, an internal source code audit was conducted. A critical typo was identified in the menu transition controller script `IntroLevel.cs`. The initialization callback function was declared as lowercase void `onenable()`. According to Unity lifecycle documentation, active callback functions must be declared precisely in PascalCase as `OnEnable()`. The previous declaration caused the function to be treated as a custom method without ever being automatically invoked by the Unity engine when the scene started. Fixing the declaration to `OnEnable()` successfully restored the automated asynchronous scene transition flow.

4. CONCLUSION

4.1. Conclusion

The EcoWaste-AR application has been successfully designed and implemented using Unity 6 and Vuforia Engine SDK as an interactive learning medium for waste classification. Based on functional testing, the image-based marker tracking system is capable of recognizing three types of waste cards (Organic, Inorganic, B3) and rendering low-poly 3D models stably within a distance of 10–60 cm, camera angles $> 30^\circ$, and light intensities > 10 lux. The addition of visual feedback such as easing logo animations, scale-pop buttons, and billboard information labels is proven to enhance the app's ergonomics and readability in real-time, achieving a stable rendering performance at 60 FPS.

4.2. Suggestions

Several developments suggested for future work include:

1. Adding gamification features, such as an interactive waste-sorting mini-game with score tracking to improve learning motivation.
2. Integrating the system with a cloud database to store users' learning progress data.
3. Increasing the variety of 3D waste models in each category to expand the educational content presented.

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