

DEVELOPMENT OF THE SWARA AUGMENTED REALITY APPLICATION FOR WASTE SORTING EDUCATION IN ELEMENTARY SCHOOLS

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Abstract— The prevailing issue of suboptimal waste management significantly contributes to environmental pollution. While early environmental education is crucial for instilling the habit of waste sorting, conventional methods often fail to engage elementary school students. To address this, this study developed an innovative learning medium integrating Augmented Reality (AR) to provide a more interactive and enjoyable learning experience. This research employed using the ADDIE model (Analysis, Design, Development, Implementation, Evaluation). Initial Analysis identified user needs, leading to the Design of an application incorporating AR for interactive visualization for waste classification and marker creation. This development resulted in the "Smart Waste Sorting Augmented Reality" (SWARA) learning medium. Implementation involved trials in elementary schools in Bekasi Regency, with sampling determined by simple random sampling and the Slovin formula. The developed SWARA application features three waste marker categories: organic, Inorganic, and hazardous waste. Trial results demonstrated that the application successfully improved students' waste sorting accuracy and enhanced their knowledge of recycling. Evaluation using the User Experience Questionnaire (UEQ) across six main scales (Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation, Novelty) showed an overall average result in the "Good" category. The highest scores were for Perspicuity (1.78) and Efficiency (1.74), while the lowest was Novelty (1.15), though still within the good range. The findings demonstrate that AR based learning significantly enhances students' conceptual understanding, engagement, and practical skills in waste sorting compared to conventional learning methods.

Keywords: ADDIE, Artificial Intelligence, Augmented Reality, UEQ, Waste Sorter.

Intisari— Permasalahan utama yang diangkat adalah pengelolaan sampah yang belum optimal sehingga berkontribusi pada pencemaran lingkungan. Pendidikan lingkungan sejak dini dinilai penting untuk menumbuhkan kebiasaan memilah sampah, namun metode konvensional kurang menarik bagi siswa SD. Oleh karena itu, penelitian ini mengembangkan media pembelajaran inovatif berbasis Augmented Reality (AR). Teknologi ini diharapkan mampu memberikan pengalaman belajar yang lebih interaktif, menyenangkan dilingkungan Sekolah Dasar (SD). Penelitian menggunakan pendekatan Research and Development (R&D) dengan model ADDIE (Analysis, Design, Development, Implementation, Evaluation). Analisis dilakukan untuk mengidentifikasi kebutuhan pengguna, lalu desain aplikasi disusun dengan integrasi AR untuk visualisasi interaktif untuk klasifikasi sampah dan pembuatan marker. Pengembangan aplikasi menghasilkan media pembelajaran "Smart Waste Sorting Augmented Reality" atau SWARA. Implementasi dilakukan melalui uji coba di sekolah dasar dengan metode User Experience Questionnaire (UEQ), sementara evaluasi dilakukan untuk mengukur efektivitas dan kepuasan pengguna. Lokasi penelitian di Kabupaten Bekasi, dengan pengambilan sampel menggunakan simple random sampling dan perhitungan dengan rumus Slovin. Aplikasi SWARA berhasil dikembangkan dengan tiga kategori marker sampah: organik, anorganik, dan Sampah B3. Hasil uji coba menunjukkan aplikasi dapat meningkatkan akurasi pemilahan sampah siswa serta memperkaya pengetahuan tentang daur ulang. Evaluasi menggunakan UEQ pada 6 skala utama (Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation, Novelty) menunjukkan hasil rata-rata



kategori "Good". Nilai tertinggi adalah Perspicuity (1,78) dan Efficiency (1,74), sedangkan skor terendah adalah Novelty (1,15), namun tetap berada pada kategori baik. Penelitian ini menawarkan integrasi media pembelajaran berbasis AR-AI yang menggabungkan klasifikasi sampah secara real-time dengan visualisasi AR berbasis marker yang dirancang khusus untuk pendidikan lingkungan di sekolah dasar. Temuan penelitian menunjukkan bahwa pembelajaran berbasis AR-AI secara signifikan meningkatkan pemahaman konseptual, keterlibatan, dan keterampilan praktis siswa dalam pemilahan sampah dibandingkan dengan metode pembelajaran konvensional.

Kata Kunci: ADDIE, Kecerdasan Buatan, Pemilah Sampah, Realitas Tertambah, UEQ.

INTRODUCTION

The problem of suboptimal waste management contributes to worsening environmental pollution. One effective way to mitigate this negative impact is through early environmental education. However, conventional approaches to teaching waste sorting to elementary school students are still less engaging and do not provide an interactive learning experience. Therefore, innovative technology-based solutions are needed that can improve learning effectiveness and foster the habit of independent waste sorting from an early age. By utilizing Augmented Reality (AR) and Artificial Intelligence (AI) technology, students can gain a more visual, interactive, and practice-based learning experience.

Through the use of this technology, students are invited to learn waste sorting through fun and innovative methods. Effective waste management is a major challenge in developing cities, including Makassar, with increasing waste volumes and low public awareness [1]. Increasing Public Knowledge and Awareness The counseling efforts have succeeded in increasing public awareness of the dangers of waste if not managed properly [2]. The waste problem is a global issue that is increasing along with population growth and human consumption. Based on a report from the World Bank (2022), global waste production is expected to increase to 3.40 billion tons by 2050 [3]. In Indonesia, data from the Ministry of Environment and Forestry (2023) shows that Indonesia produces around 68 million tons of waste per year, with a low recycling rate [4]. One of the main causes of this problem is the low public awareness, especially children, of the importance of sorting waste from an early age [5], [6], [7].

Effective waste management remains a significant challenge in many developing regions, including Indonesia. This research aims to enhance environmental education for elementary students by integrating technology-based learning through AR and AI. The study hypothesizes that the integration of AR and AI in learning media significantly improves students' understanding and

motivation in waste sorting compared to conventional methods. By visualizing real-world waste classification through AR and automating recognition with AI, students engage in a more interactive. This approach supports Accordingly, the explicit hypothesis of this study is that: Students who learn waste-sorting concepts using AR-AI-based learning media will achieve significantly higher understanding and motivation compared to students who receive conventional classroom instruction. By visualizing real-world waste classification through AR and automating object recognition using AI, students are expected to engage in a more interactive, contextual, and experiential learning process. This approach supports sustainable awareness formation from an early age.

The importance of instilling character education is carried out to every student at every level through the Waste Bank. The Waste Bank is one of the media in instilling two of the eighteen character education values of the Ministry of Education and Culture, namely creativity and environmental care [8]. However, conventional, theory-based classroom learning methods are often ineffective in fostering sustainable awareness and habits. In this context, the use of digital technologies such as AR offers an innovative approach to environmental education for elementary school students. AR can provide interactive experiences that increase student interest and engagement in the classroom.

Furthermore, the development of AR and AI-based educational technology aligns with the government's program to improve digital literacy and technology-based education in elementary schools. The Indonesian government, through the Ministry of Education, Culture, Research, and Technology, continues to encourage innovation in technology-based learning methods to support the achievement of "Merdeka Belajar" (Freedom to Learn). Therefore, this research is highly relevant in supporting national education policy while also providing concrete solutions to the problem of waste management from an early age.

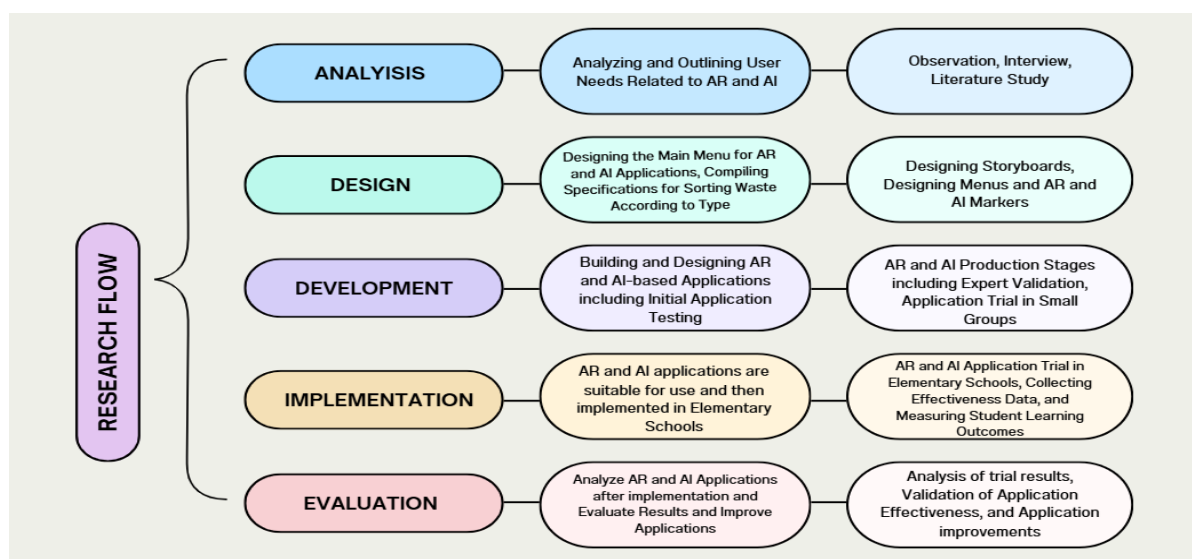
Augmented reality (AR) technology to enhance learning and understanding of hazardous waste separation, while raising awareness of the dangers, particularly primary school students [9]. AI and AR techniques have been used by many researchers to improve waste management and promote sustainability [10]. To answer the formulated problems, this study adopts an educational technology (EdTech) based approach that integrates AR and Artificial Intelligence AI in learning waste sorting in previous research using AR technology can be used as a suitable and interactive media in classroom learning, especially at the Elementary School level [11], and students have new knowledge on how to manage waste according to its type [12]. To test the stated hypothesis, this study employs experimental and control groups. The developed application utilizes AR to display interactive visual information about waste types, while the AI component uses machine-learning classification to identify waste from real-time images captured by the user's device. Trials will be conducted in several elementary schools, comparing learning outcomes and motivation between the experimental group (AR-AI application) and the control group (conventional learning methods).

Research in the field of technology-based environmental education has experienced rapid development in recent years. Several recent studies have shown that the use of digital technology in education has a significant positive impact on learning effectiveness. In relevant research, it was found that AR can improve students' conceptual understanding through visual and interactive learning experiences [13]. Meanwhile, the use of

artificial intelligence (AI) to personalize learning experiences has opened a new chapter in the world of education. This technology allows learning systems to dynamically adapt to the needs, abilities, and preferences of each student [14]. In addition, several studies highlight the importance of digital technology in increasing environmental awareness and understanding of the concept of waste sorting among students.

MATERIALS AND METHODS

This research uses the Research and Development (R&D) method with the ADDIE (Analysis, Design, Development, Implementation, Evaluation) model . The stages of the ADDIE model are presented in the research flowchart in Figure 1. The ADDIE framework in this study is not only presented as a procedural sequence but analyzed in its role as the core instructional design model guiding the development of the SWARA learning media. Figure 1 illustrates the conceptual progression of the ADDIE stages, beginning with Analysis, which identifies user needs and key literature on AR-AI-supported waste education. The Design stage specifies technological components, interaction flow, marker structure, and AI-based classification requirements. The Development stage focuses on constructing and testing the AR-AI modules. The Implementation stage includes classroom trials and user-experience measurement using the UEQ instrument. Finally, the Evaluation stage synthesizes empirical findings to refine system functionality and instructional effectiveness.



Source: (Research Result, 2025)

Figure 1. Research Flow using the ADDIE Model



The caption for Figure 1 of the research flow is as follows:

Analysis: Identifying user needs and conducting literature studies related to the use of AR and AI in learning about types of waste.

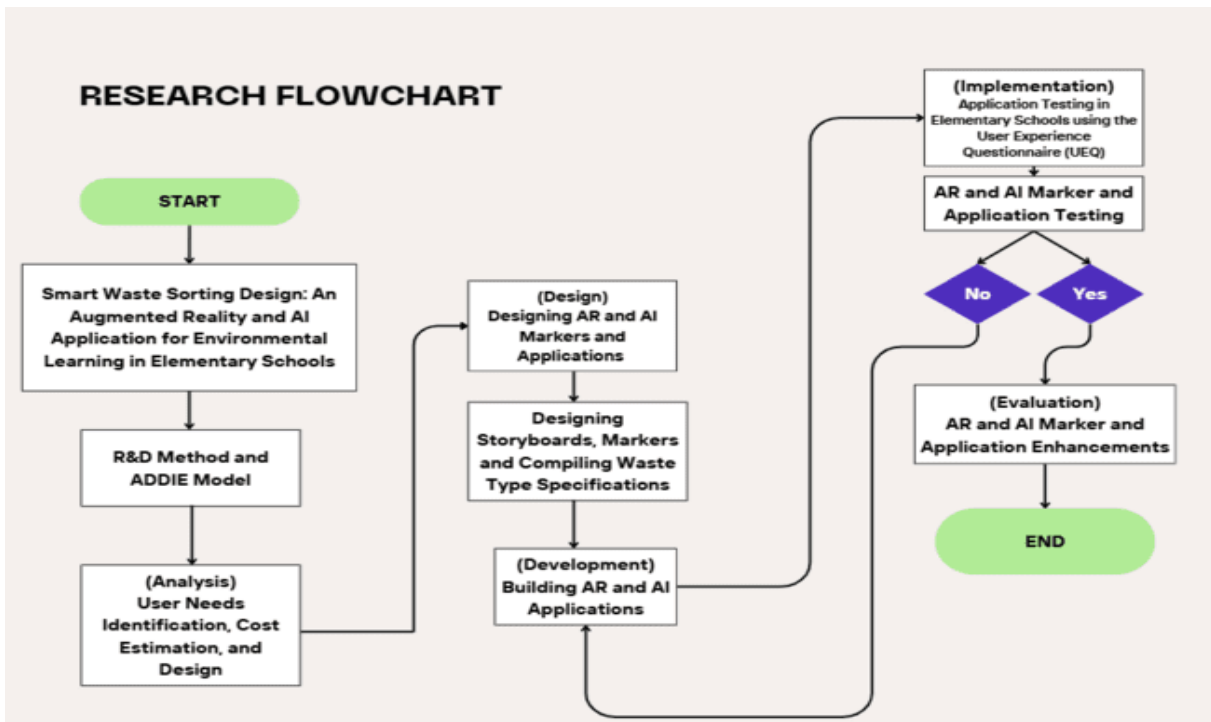
Design: Design the main features of the application, determine the technology used, and compile specifications for the waste sorting system based on its type.

Development: Implementing AR and AI-based applications, including initial system programming and testing.

Implementation: Application trials in elementary schools, collecting effectiveness data, and measuring student learning outcomes. Testing using the User Experience Questionnaire (UEQ) [15], [16].

Evaluation: Analysis of trial results, validation of application effectiveness, and system improvements.

The research flow diagram that explains the initial stages to the end of the research process is presented in Figure 2 below:



Source: (Research Result, 2025)

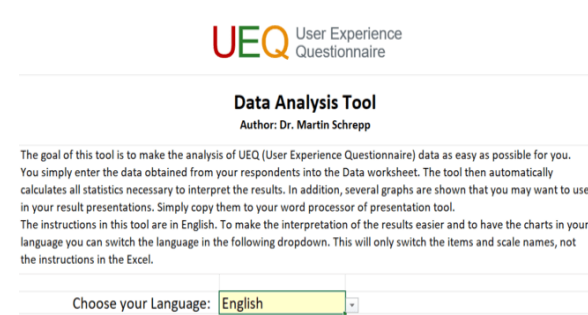
Figure 2. Research Flowchart

The research flowchart in Figure 2 represents the stages of designing an AR and AI waste sorting application, starting with Analysis, which involves analyzing user needs, costs, and design. The second stage is Design, which involves designing markers and AR and AI applications. The third stage is Development, which involves building AR and AI applications. The fourth stage is Implementation, which involves testing markers and applications using User Experience Questionnaires (UEQ). The fifth stage is Evaluation, which involves refining applications that fail to run during testing.

The UEQ is a standard questionnaire for measuring user experience of an interactive product quickly and reliably. Consists of 26 items (antonym word pairs) that use a semantic differential scale from -3 to +3. The six main scales

measured are: 1)Attractiveness, 2)Perspicuity, 3)Efficiency, 4)Dependability, 5)Stimulation and 6)Novelty.

To measure user experience using the UEQ tool analysis data shown in figure 3.



Source: (Research Result, 2025)

Figure 3. UEQ Data Analysis Tool

The hardware and software prepared to design the smart waste sorting application can be seen in Table 1 as follows:

Table 1. Research Hardware and Software

hardware	Software
<p>Laptop: Core I5, Intel HD 630 + Nvidia GT 1050 Ti 4GB for 3D Object Design (Marker Design)</p>	<p>Unity 3D: Unity is designed for developers to create responsive, high-performance 3D content for multiple platforms.</p> <p>SeaArt AI: an Artificial Intelligence (AI) based application used to create, edit, modify images automatically for made animation video and marker.</p> <p>Marker: a visual pattern or image used as a reference for the system to detect, track, and overlay virtual objects in the real world.</p> <p>Vuforia SDK: Augmented Reality Development Kit for mobile devices that can be used to create augmented reality applications.</p> <p>AR Foundation is a cross platform framework developed by Unity that enables developers to build Augmented Reality (AR) applications for multiple platforms using a single codebase. It acts as an abstraction layer that connects Unity with underlying AR technologies such as ARCore for Android and ARKit for iOS.</p>
<p>Smartphone: Qualcomm Snapdragon 720G SM7125, OS Android (11), RAM 6GB</p>	

dimensions. UEQ is a standardized instrument widely applied in Human-Computer Interaction (HCI) research due to its ability to capture both pragmatic (usability) and hedonic (emotional) aspects of user experience efficiently. The six UEQ dimensions are attractiveness, perspicuity, efficiency, dependability, stimulation and novelty.

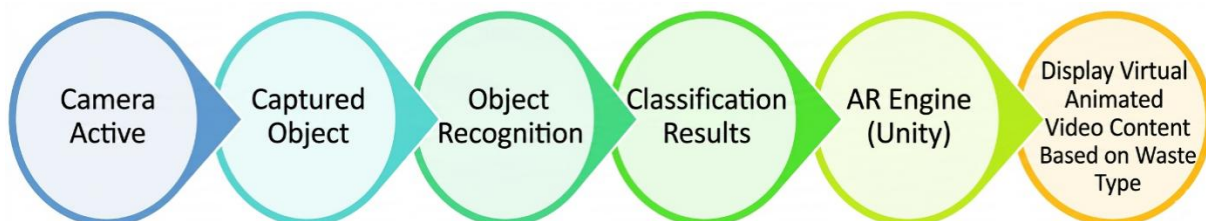
The SWARA application was developed using Unity 3D integrated with Vuforia SDK for marker-based AR tracking. Testing revealed several implementation challenges, including marker detection sensitivity under low-light conditions, camera latency averaging 0.8 seconds per frame, and reduced accuracy on devices with less than 3GB RAM. To address these issues, the marker design incorporated high-contrast black-and-white templates, and texture compression was applied to reduce processing lag. Future versions will consider migrating to markerless AR to increase flexibility across devices.

Beyond reporting descriptive UEQ results, a more critical interpretation situates SWARA's performance within broader findings from similar AR-based educational technologies. Studies on AR science learning platforms typically report high scores in Attractiveness and Stimulation, but moderate scores in Efficiency due to device limitations and rendering delays. Compared with these trends, SWARA demonstrates competitive performance: its Attractiveness and Novelty ratings align with previous AR applications used in environmental education, indicating strong user engagement. However, the slightly lower Efficiency score reflects constraints also observed in comparable systems that rely on marker-based tracking. This suggests that SWARA's usability aligns with the strengths and limitations commonly found in AR learning tools, and that improvements—such as optimizing rendering pipelines or adopting markerless tracking—could elevate performance further. Thus, the UEQ results not only validate SWARA's user experience but also highlight its position relative to existing technologies, reinforcing the need for iterative advancements in AR-AI educational systems.

Source: (Research Result, 2025)

RESULTS AND DISCUSSION

This study employed the ADDIE model consisting of Analysis, Design, Development, Implementation, and Evaluation stages. The software used includes Unity 3D for development, Vuforia SDK for AR rendering, and SeaArt AI for generating visual content. The UEQ method was used to evaluate user experience across six



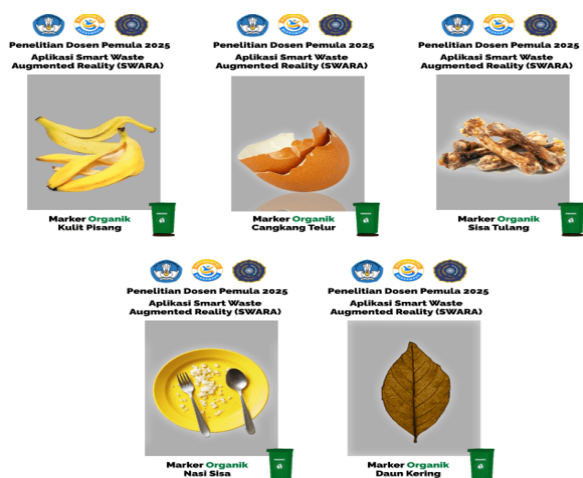
Source: (Research Result, 2025)

Figure 4. SWARA Application Workflow



The SWARA program, which combines artificial intelligence (AI) and augmented reality (AR) to enhance waste sorting education, is shown in figure 4. The procedure starts with turning on the device's camera to take pictures of actual garbage items. Then, AI algorithms are used to recognize the things' visual features. After the garbage is classified by the system into categories such as organic, inorganic, or hazardous waste, the AR engine (Unity) processes the classification findings to display interactive animated material based on the waste type that was recognized.

The next step is marker creation. In the context of Augmented Reality (AR), a marker is a visual marker in the form of a pattern, image, or specific object that the AR system uses as a reference to display virtual elements in the real world. Markers are typically two-dimensional images (e.g., black-and-white checkered patterns, QR codes, or logos) that a device's camera can recognize. When the camera detects a marker, the AR application calculates its position, orientation, and scale so that digital objects (such as text, 3D animations, or interactive models) can be accurately displayed on top of it. In other words, markers act as a bridge between the real world and digital content, as seen in Figure 5. The SWARA application integrates AR-based waste visualization and AI-assisted classification. The character design and markers enhance learning engagement, while the app's educational framework emphasizes environmental awareness. From a technical standpoint, AR markers for organic, inorganic, and hazardous waste enable interactive feedback when scanned. From a pedagogical perspective, this visualization reinforces conceptual understanding and student motivation.



Source: (Research Result, 2025)

Figure 5. Organic Waste Marker

Figure 5 is a marker. Organic waste is a type of waste derived from living things, both plants and animals, that is easily decomposed naturally through biological processes, such as decomposition by microorganisms. Examples include food scraps, vegetables, fruit, dry leaves, grass, paper, and even animal waste. Because of its easily decomposed nature, organic waste can be processed into compost or natural fertilizer that is beneficial for plants. However, if left to pile up without processing, organic waste can produce unpleasant odors, attract pests, and pollute the environment [17], [18], [19].

Figure 6 is a marker for inorganic waste. Inorganic waste is waste derived from non-biological or synthetic materials, such as plastic, metal, glass, and electronics, which are very difficult to decompose naturally and therefore have the potential to pollute the environment in the long term. This type of waste requires special management through recycling methods, energy recovery, and a circular economy approach to minimize its impact on ecosystems and human health. For example, post-consumer plastic requires thermochemical processing such as gasification, while e-waste (electronic waste) requires the separation of valuable materials such as metal and glass to prevent heavy metal contamination [20].



Source: (Research Result, 2025)

Figure 6. Inorganic Waste Marker

Figure 7 is a marker for Hazardous waste which is flammable and toxic from households also includes leftover medicines, cleaning products, pesticides and product packaging which has toxic properties [21].



Source: (Research Result, 2025)
Figure 7. Hazardous Waste Marker

The use of markers in AR has several advantages, including the stability of digital object displays because the system has a clear reference point. This makes interactions more accurate, especially in educational applications, games, and promotional media. However, markers also have limitations, such as being usable only if the camera can clearly see the marker and there is adequate lighting. Therefore, markerless AR is becoming more widely used, but marker-based AR remains popular due to its simplicity, accuracy, and suitability for various learning and demonstration needs.



Source: (Research Result, 2025)
Figure 8. SWARA Application (Main Menu Interface)

Figure 8 is a swara application with 4 menus consisting of an AR scan which activates the camera to capture objects through markers according to the type of waste, the second menu, namely the explanation, is an explanation of the application

while the about us menu explains the names of researchers and research members and thanks to the Ministry of Higher Education, Science and Technology (Kemendiknas) for funding in 2025 and the exit menu to exit the SWARA application. The results of the AR scan present a virtual animated video in sorting waste which can be seen in figure 9.



Source: (Research Result, 2025)
Figure 9. AR Scan Results of Organic Waste

To provide contextual insight into the performance of the proposed system, the SWARA application was descriptively compared with two previously reported AR-based learning systems, namely the AR-based Hazardous Waste Learning System[9] and the Waste Detection AR Tool [10] The comparison was conducted at a conceptual level based on reported user experience evaluation results in the respective studies rather than through a direct experimental benchmark. Differences in participant characteristics, evaluation settings, and implementation contexts between the studies should therefore be considered when interpreting the comparison.

Based on the available reports, the user experience results indicate that SWARA demonstrates comparable usability performance. In particular, the SWARA application achieved slightly higher scores in the Efficiency and Perspicuity dimensions of the User Experience Questionnaire (UEQ), with differences of approximately +0.12 and +0.15, respectively. However, these differences should be interpreted as indicative rather than definitive due to variations in study populations, application features, and evaluation procedures across the compared systems.

In terms of system design, the two comparison systems primarily focused on AR-based visualization to support learning engagement. In contrast, SWARA integrates AR-based interactive visualization with an AI-supported waste classification mechanism designed to improve the



accuracy of waste identification during learning activities. This integration provides an additional functional layer that may enhance the educational effectiveness of the system in elementary school environments. Overall, the comparison suggests that SWARA offers competitive usability performance while introducing a hybrid AR-AI approach that supports both interactive learning and waste classification tasks in environmental education contexts.

The study involved three public elementary schools located in Bekasi Regency, with a total of 100 participating students aged between 9 and 11 years. The sample was determined using the Slovin formula with a 10% margin of error. This sample size was considered sufficient for educational technology testing under at design conditions [22]. Questionnaires were distributed in two ways: by visiting elementary schools directly and by filling out a questionnaire link. The sampling method used was simple random sampling was the sampling technique employed, and the sample was determined using the Slovin formula in formula 1.

$$n = \frac{N}{1 + Ne^2} \quad (1)$$

$$n = \frac{14.786}{1 + 14.786 \cdot 0,1^2} \quad n = 99,99$$

Formula 1 is explained as follows:

n = sample size

N = population size

e = accuracy limit value

Table 2 explains is Waste types are grouped into organic waste that can be composted, organic waste with economic value that can be recycled, and hazardous waste.

Types of Waste	Example
Organic waste	Banana peels, chicken bones, eggshells, leftover rice, and dried leaves
Inorganic Waste	plastic packaging, plastic bottles, plastic bags, plastic cups, and beverage cans
Hazardous Waste	Used batteries, paint cans, type x, expired medication, used medicine bottles

Source: (Research Result, 2025)

Based on the calculation of formula 1, a minimum sample size of 100 was taken for processing the UEQ data analysis tool. The questionnaire results were then entered into the data based table 3. The User Experience

Questionnaire (UEQ) uses a 1–7 rating scale in the form of a semantic differential scale, consisting of pairs of contrasting adjectives (e.g., interesting–boring, easy to understand–difficult to understand). This scale allows respondents to subjectively yet measurably rate their experience with an application or interactive product. A score of 1 typically indicates the most negative assessment, a score of 7 indicates the most positive assessment, and a score of 4 is neutral. This model allows the UEQ to quickly and comprehensively gauge user impressions of the design, usability, and innovation of the product being tested.

The UEQ consists of six main dimensions: Attractiveness (the general appeal of the application), Perspicuity (ease of understanding and use), Efficiency (speed and effectiveness in achieving goals), Dependability (system reliability and consistency), Stimulation (the application's ability to motivate and engage), and Novelty (the perceived level of novelty and innovation). Using this 1–7 scale, researchers can analyze trends in user perception, compare them with international UEQ benchmarks, and identify areas of improvement and performance. UEQ assessment results are often used in research and development of digital products to improve the quality of user experience and ensure that applications meet the needs of target users is presented in table 3 .

Table 3. UEQ Questionnaire Scale

No	Item	1	2	3	4	5	6	7	Scale
1	Annoying/Enjoyable								Attractiveness
2	Not Understandable/Understandable								Perspicuity
3	Dull/Creative								Novelty
4	Difficult To Learn/Easy To Learn								Perspicuity
5	Inferior/Valuable								Stimulation
6	Boring/Exciting								Stimulation
7	Not Interesting/Interesting								Stimulation
8	Unpredictable/Predictable								Dependability
9	Slow/Fast								Efficiency
10	Conventional/Inventive								Novelty
11	Obstructive/Supportive								Dependability
12	Bad/Good								Attractiveness
13	Complicated/Easy								Perspicuity

No	Item	1	2	3	4	5	6	7	Scale
14	Unlikable/Pleasant								Attractiveness
15	Usual/Leading Edge								Novelty
16	Unpleasant/Pleasant								Attractiveness
17	Not Secure/Secure								Dependability
18	Demotivating/Motivating								Stimulation
19	Does Not Meet Expectations/Meets Expectations								Dependability
20	Inefficient/Efficient								Efficiency
21	Confusing/Clear								Perspicuity
22	Impractical/Practical								Efficiency
23	Cluttered/Organized								Efficiency
24	Unattractive/Attractive								Attractiveness
25	Unfriendly/Friendly								Attractiveness
26	Conservative/Innovative								Novelty

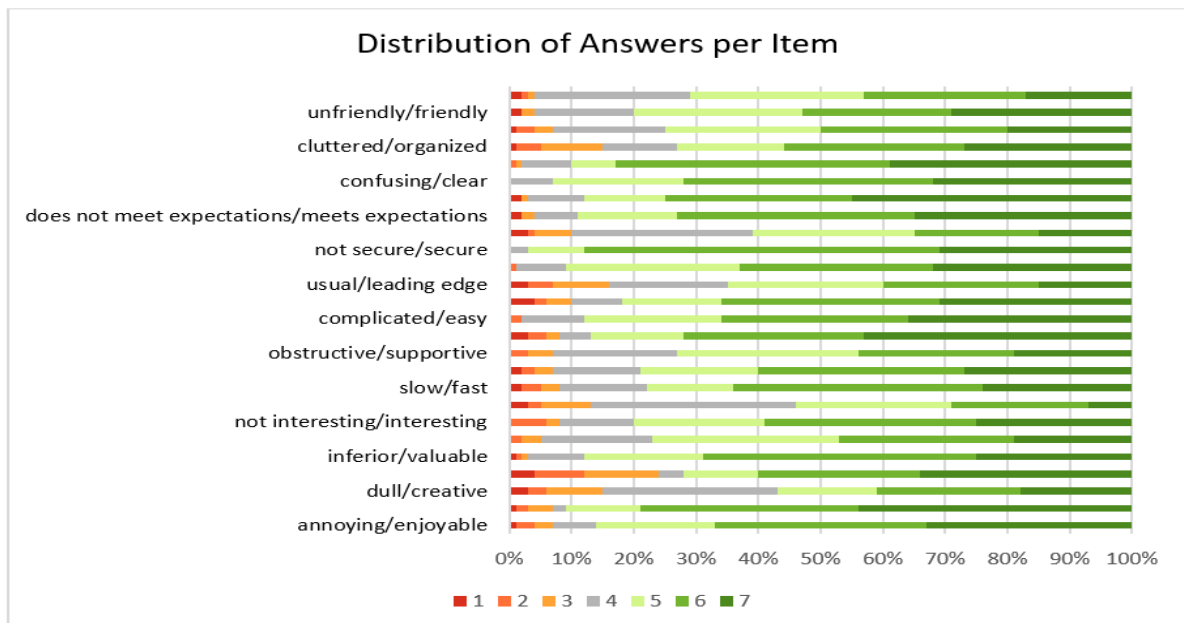
Source: (Research Result, 2025)

Every aspect of the user experience can be comprehensively measured using the UEQ scale, which encompasses six main dimensions:

Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation, and Novelty. The average score for each scale is then compared with the UEQ Tool benchmark score to determine whether the tested application falls within the categories of Very Good, Good, Above Average, Below Average, or Poor.

This comparison provides an objective overview of the application's strengths and weaknesses, which can serve as a basis for further development evaluation. By using international benchmarks, the results obtained are not only relevant in the local context but also comparable with similar research in various countries. After obtaining the questionnaire results, a distribution analysis of the responses per item was performed, and then the average (mean) score for each word pair was calculated.

This distribution shows respondents' tendency to evaluate the application, whether it was predominantly positive, neutral, or negative. The obtained mean scores are then presented graphically in Figure 10 to facilitate visualization and interpretation of the results. This data presentation is very important because it helps researchers understand user perception patterns in more detail, while also providing an empirical basis for drawing conclusions regarding the level of application acceptance and its effectiveness as an AR and AI-based interactive learning medium.



Source: (Research Result, 2025)

Figure 10. Distribution of Answers per item

Table 4 shows the results of the comparison of application benchmarks with 6 scales showing the average value with an interpretation of 10%

better results expressed as Good, the dark green graph is presented in Figure 11.



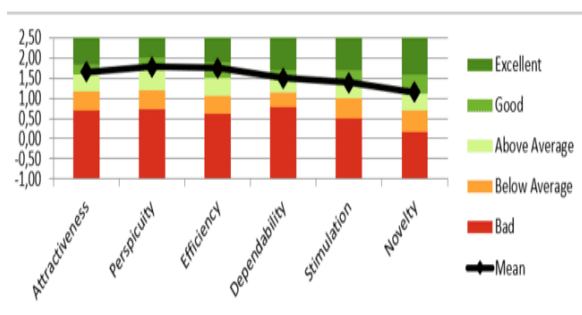
Table 4. SWARA Application Benchmark Results

Scale	Mean	Comparison to benchmark	Interpretation
Attractiveness	1,65	Good	10% of results better, 75% of results worse
Perspicuity	1,78	Good	10% of results better, 75% of results worse
Efficiency	1,74	Good	10% of results better, 75% of results worse
Dependability	1,50	Good	10% of results better, 75% of results worse
Stimulation	1,39	Good	10% of results better, 75% of results worse
Novelty	1,15	Good	10% of results better, 75% of results worse

Source: (Research Result, 2025)

Test results using the User Experience Questionnaire (UEQ) showed that the SWARA app achieved an average score of Good on six main scales: Attractiveness (1.65), Perspicuity (1.78), Efficiency (1.74), Dependability (1.50), Stimulation (1.39), and Novelty (1.15). The highest scores were for the Perspicuity aspect, indicating the app is easy for students to understand and use, and the Efficiency aspect, indicating the app's ability to provide information quickly and practically.

A high Attractiveness score also indicates that students find the app enjoyable and engaging, thus increasing their motivation to learn. Overall, these results demonstrate that SWARA is not only suitable for use but also provides a positive and accessible learning experience for elementary school users.



Source: (Research Result, 2025)

Figure 11. SWARA Application Benchmark

Meanwhile, the Dependability score (1.50) confirms the app's reliability in providing feedback according to its intended function. The Stimulation aspect (1.39) indicates that although the application is able to motivate and encourage students' interest in learning, its development can still be improved to be more interactive and varied. The lowest score is in Novelty (1.15), which indicates that the application's innovation still needs to be further developed to provide a new, more unique experience for students. However, all scores in the

"Good" category confirm that the SWARA application has met user experience standards and can be implemented effectively in elementary school environments as an interactive learning medium based on AR and AI.

A comparative analysis of UEQ results shows that SWARA's performance aligns with similar AR-based educational tools such as those developed [9], [23]. The app achieved high Perspicuity (1.78) and Efficiency (1.74) scores, indicating usability and clarity advantages, though its Novelty score (1.15) suggests potential for innovation through gamification. Overall, SWARA demonstrated a balanced performance, providing a solid foundation for environmental learning integration in primary education.

Beyond the User Experience Questionnaire (UEQ) an additional evaluation was conducted to assess students' learning outcomes related to waste sorting concepts. A pre-test and post-test design was implemented involving 100 elementary school students from three schools in Bekasi Regency. The assessment instrument consisted of ten multiple-choice questions covering waste classification, recycling concepts, and proper waste disposal practices.

The instrument was reviewed by two environmental education experts to ensure content validity, and each correct answer was scored as one point, resulting in a maximum score of 100. The pre-test was administered before students were introduced to the SWARA application to measure their initial understanding of waste sorting concepts. Afterward, students participated in a learning session using the SWARA application for approximately 30 minutes, where they interacted with AR-based visualizations and waste classification activities.

The post-test was conducted immediately after the learning session using the same instrument to measure changes in students' understanding. To minimize testing effects, the order of questions was randomized in the post-test while maintaining the same content. The results show that the mean learning score increased from 63.5 in the pre-test to 82.1 in the post-test. A paired-sample t-test analysis yielded $t(99) = 11.28$, $p < 0.001$, indicating a statistically significant improvement in students' understanding of waste sorting concepts after using the SWARA application. These findings suggest that the SWARA application not only provides a positive user experience but also contributes to measurable improvements in students' learning outcomes in environmental education.

CONCLUSION

This study confirms that the Smart Waste Sorting Augmented Reality (SWARA) application is a feasible AR-AI-based learning medium that supports interactive environmental education and fosters early waste-sorting awareness among elementary school students. The UEQ findings indicate that high Perspicuity and Efficiency reflect SWARA's ability to deliver clear instructional guidance and practical interaction, which are essential for technology-assisted learning in primary education contexts. The application demonstrates broader potential to support environmental education programs and reinforce national waste management initiatives by introducing experiential, technology-enhanced learning from an early age. Nevertheless, this study acknowledges several limitations of the current SWARA version, including its reliance on marker-based AR, sensitivity to lighting conditions, and limited adaptability across different device specifications, which may affect flexibility in diverse classroom environments. Future research is recommended to focus on improving system robustness and scalability, including the development of markerless AR and more adaptive learning features to strengthen long-term educational impact.

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REFERENCE

- [1] R. S. Wandira, G. Susanti, and A. Hans, "Paradigma Baru Pengelolaan Sampah: Peran Budaya Organisasi dan Kapabilitas Dinamis dalam Program Bank Sampah," vol. 4, no. 2, pp. 347-360, 2024, doi: 10.52423/pamarenda.v4i2.49.
- [2] M. Sa'diyah, W. H. Setyawan, A. Kumala, A. Arini, M. N. Salim, and B. Ridlwan, "Penggunaan Ide Zero Waste untuk Pengolahan Limbah Organik dan Anorganik Untuk Meningkatkan Kualitas Lingkungan Hidup", SAINSTEKNOPAK, vol. 8, pp. 123-129, Dec. 2024.
- [3] S. Kaza, L. Yao, P. BhadaTata, and F. Van Woerden, "What a Waste 2.0 A Global Snapshot of Solid Waste Management to 2050," *International Bank for Reconstruction and Development / The World Bank*, 2022. [Online]. Available: <https://datatopics.worldbank.org/what-a-waste/>. [Accessed: 06-Apr-2025].
- [4] Kementerian Lingkungan Hidup dan Kehutanan, "KLHK Ajak Masyarakat Kelola Sampah Organik Jadi Kompos," *Kementerian Lingkungan Hidup dan Kehutanan*, 2023. [Online]. Available: <https://ppid.menlhk.go.id/berita/siaran-pers/7061/klhk-ajak-masyarakat-kelola-sampah-organik-jadi-kompos>. [Accessed: 06-Apr-2025].
- [5] N. K. A. Candrawati, K. J. Mahadewi, N. K. I. D. Yanti, I. W. A. Sumartana, and N. P. A. Nilayanti, "Pengadaan Tempat Sampah Sebagai Wujud Implementasi Pemilahan Sampah Di Desa Marga Dajan Puri," *Kumawula J. Pengabd. Kpd. Masy.*, vol. 5, no. 3, pp. 485-493, 2022, doi: 10.24198/kumawula.v5i3.38146.
- [6] T. A. Purnomo and D. Sunarsih, "Sosialisasi Pemilahan Sampah Organik dan Non-organik di SDN Banjarharjo 07 Jawa Tengah," *J. Abdi Masy. Indones.*, vol. 3, no. 2, pp. 465-472, 2023, doi: 10.54082/jamsi.687.
- [7] R. Febriyanti, N. V. A. Rahayu, W. D. Pitaloka, A. Yakob, and M. Samsuri, "Edukasi Pemilahan Sampah sebagai Upaya Penanganan Masalah Sampah di SD Muhammadiyah Baitul Fallah Mojogedang," *Bul. KKN Pendidik.*, vol. 5, no. 1, pp. 37-45, 2023, doi: 10.23917/buletinkndik.v5i1.11840.
- [8] N. P. Wina Maryuni, "Penanaman Pendidikan Karakter Melalui Pengelolaan Bank Sampah di Lingkungan Sekolah," *Metta J. Ilmu Multidisiplin*, vol. 4, no. 1, pp. 126-139, 2024.
- [9] K. Kemavuthanon, "An Augmented Reality-Based Hazardous Waste Management Learning System: A Case Study of Elementary School Students in Chiang Rai Province," in *2025 Joint International Conference on Digital Arts, Media and Technology with ECTI Northern Section Conference on Electrical, Electronics, Computer and Telecommunications Engineering (ECTI DAMT & NCON)*, pp. 394-399, 2025, doi:



- 10.1109/ECTIDAMTNC64748.2025.10962102.
- [10] Q. Sun, I.-H. Hsiao, and S.-Y. Chien, "Immersive Educational Technology for Waste Management Learning: A Study of Waste Detection and Feedback Delivery in Augmented Reality," in *Communications in Computer and Information Science, Springer*, vol. 1835, pp. 509–515, 2023, doi: 10.1007/978-3-031-36001-5_66.
- [11] R. S. Untari, F. N. Hasanah, M. D. K. Wardana, and M. I. Jazuli, "Pengembangan Augmented Reality (AR) Berbasis Android Pada Pembelajaran Pemodelan Bangun Ruang 3D," *J. Pendidik. Teor. Penelitian, dan Pengemb.*, vol. 7, no. 5, p. 190, 2022, doi: 10.17977/jptpp.v7i5.15238.
- [12] F. Anis, N. Dias, L. Dewi, and Z. Finali, "Edukasi Pemilahan Sampah untuk Meningkatkan Karakter Peduli Lingkungan Siswa SD Labschool UNEJ," vol. 4, no. 2, pp. 500–506, 2024, doi: 10.54259/pakmas.v4i2.3060.
- [13] H. B. A. Jayawardana, "Strategi Inovatif Pemanfaatan Teknologi Digital dalam Pendidikan Biologi untuk Meningkatkan Hasil Belajar Siswa," *J. Educ. Sci. E-Learning*, vol. 1, no. 2, pp. 159–165, 2024.
- [14] Arnadi, Aslan, and A. Y. Vandika, "PENGUNAAN KECERDASAN BUATAN UNTUK PERSONALISASI PENGALAMAN BELAJAR," *J. Ilmu Pendidik dan Kearifan Lokal*, vol. 4, no. 5, pp. 369–380, 2024.
- [15] Z. Muhammad Arkan, A. Gandhi, and A. P. Kurniati, "meningkatkan aspek-aspek User Experience berdasarkan pengukuran UEQ pada aplikasi Xyz II," *e-Proceeding Eng.*, vol. 10, no. 5, pp. 5080–5086, 2023.
- [16] M. Nadindra Fawwaz, A. P. Kurniawan, and A. Sularsa, "Pembuatan Konten Model 3D Augmented Reality Pada Aplikasi Pengenalan Jenis Sampah Untuk Anak 5 Tahun," *e-Proceeding Appl. Sci.*, vol. 9, no. 3, pp. 1383–1390, 2023.
- [17] I. M. Gunamantha, N. W. Yuningrat, and M. V. Oviantari, *Pengelolaan Sampah Organik; Pemulihan Sumber Daya dan Sirkularitas. Mobius*, 2024.
- [18] L. W. Y. Dewi and K. L. Kusnita, "Edukasi Pemilahan Sampah Sejak Dini di SDN 1 WONGAYA GEDE," *J. Mandala Pengabd. Masy.*, vol. 4, no. 1, pp. 166–170, 2023, doi: 10.35311/jmpm.v4i1.189.
- [19] R. Wulandari, M. R. Ariwibowo, Taryo, and G. Ananda, "Design Smart Trash Based On the Inductive Proximity Sensor," *Int. J. Multidiscip. Approach Res. Sci.*, vol. 2, no. 01, pp. 194–200, 2024, doi: <https://doi.org/10.59653/ijmars.v2i01.394>.
- [20] R. Hasanzadeh and P. Mojaver, *Plastic waste treatment and management: Gasification processes*. Cham, Switzerland: Springer, 2023.
- [21] W. D. Yantini, I. Made, and W. Widyarsana, "Identifikasi dan Proyeksi Timbulan Sampah Mengandung B3 Rumah Tangga di DKI Jakarta," *J. Serambi Eng.*, vol. X, no. 1, pp. 11960–11967, 2025.
- [22] Badan Pusat Statistik Jawa Barat, *Provinsi Jawa Barat dalam Angka 2024*. Bekasi: BPS Provinsi Jawa Barat, 2024.
- [23] Q. Sun, S. Chien, and I. Hsiao, "Learning Waste Management from Interactive Quizzes and Adaptive GPT-guided Feedback," in *CEUR Workshop Proceedings*, pp. 1-8, 2023.