Augmented Reality Development for Garbage Sortation Education for Children

Devi Afriyantari Puspa Putri[1], Nisa Dwi Septiyanti[2], Endah Sudarmilah[3], Diah Priyawati[4]
Informatics Engineering Department, Universitas Muhammadiyah Surakarta, Surakarta, Indonesia[1, 3, 4]
Informatics Department, Universitas Muhammadiyah Karanganyar, Karanganyar, Indonesia[2]

***Abstract*—The global crisis problem related to climate change, one of the main factors is the accumulation of waste which is getting higher every day. One effective way to reduce the accumulation of waste is by sorting the waste and recycling the waste. However, the waste sorting process in Indonesia is still less effective because only 1.4% can be processed and sorted. One of the biggest causes is a lack of knowledge regarding the types of waste that exist. Based on these problems, the aim of this research is: to create augmented reality-based waste sorting educational technology which is expected to increase knowledge of types of waste and increase environmentally conscious behavior. In addition, the ADDIE development model is used for the research methods that will be used. This research has successfully built an Augmented Reality sorting waste for mobile application and received a good rating on SUS questionnaire and consider acceptable with average score 84.5 out of 100.**

***Keywords*—Augmented reality; pemilahan sampah; Unity3D; vuforia**

I. INTRODUCTION

In the current era's advancements, it positively impacted the improvement of human living standards. However, these advancements also caused the global crisis of climate change [1]. One of the factors influencing climate change is the ever-increasing accumulation of waste [2]. This occurs because the decomposition process of waste, primarily produces carbon dioxide and methane [3], [4]. These gases contribute significantly to the greenhouse effect, that is one of the primary causes of global warming [5], [6], [7]. Besides environmental impacts, plastic waste negatively affects ecosystems and can alter soil structure due to physical and chemical processes resulting from waste accumulation [8]. Despite the negative impacts of waste, the accumulation of waste, particularly plastic waste, continues to increase significantly each year [9]. This can be observed from the escalating use of plastic materials, which increased tenfold from 1% in the 1960s to 10% in 2015 [10], [11].

Waste management issues are global problems that occurring in almost every part of the world, including Indonesia [12]. This is because Indonesia ranks second in the world for waste production [13]. Waste production in Indonesia increases annually and is predicted to rise by 2-4% each year if significant efforts to reduce waste production are not implemented yet [14], [15]. Based on the research regarding the significant increase in waste, especially in Indonesia, concludes that efforts are needed to curb the growth rate of waste. One effective and crucial step in reducing waste accumulation is waste sorting [16]. According to research [17], [18], after implementing a waste sorting program, clinical waste decreased by 82%, and waste management costs were reduced by up to 60%. However, waste sorting processes in Indonesia are still ineffective, as only about 14% of the 7,000 tons of waste produced can be processed and sorted [19], [20]. Surveys also show that most people do not sort their waste correctly [21]. A lack of knowledge and proper handling are among the reasons for the low rates of waste sorting and recycling in Indonesia [22]. Waste sorting cannot be solely conducted by the government; the community also plays a significant role in the success of waste sorting education [23], which can save time and costs in the process [24].

Based on the problem about sorting waste that explain in the background. It can be concluded, that the need for educational technology related to waste sorting, particularly in Indonesia, according to the types of waste commonly encountered by the community is very important. The presence of the educational application of sorting garbage considered to help increase environmental awareness, especially regarding waste types, among the public. Additionally, it can educate users on identifying the types of waste that need to be sorted. Therefore, one solution to this problem is educating the public about the types of waste. This approach is considered effective because, according to study [25], educational processes have the potential to change public behavior. Furthermore, technology is utilized as it can effectively alter public behavior [26]. The use of games is one of the frequently used technologies today, with over one billion users [7]. Many previous studies on games have focused on negative impacts, including increased aggression, addiction to games, and difficulties in managing playtime [27], [28], [29]. However, in recent years, gamification has provided many positive impacts, such as enhancing learning motivation, raising pollution awareness, and increasing user engagement and attention as a promotional medium [30], [31], [32]. Apart from that, research on [33] also found that games on mobile application have a fairly good level of user acceptance. Another study about gamification stated that using education game able to help student learning process more effective and efficient [34]. The interest level of education game also found out in study [35] which stated that user eager to play educational games continuously. Based on the popularity of games and their positive impacts, this study developed an augmented reality (AR) application that contains educational content on waste types using gamification elements. The objective of this research to bridge gap between environmental education and technology. It demonstrates the innovative solution through AR able to addressing global challenges like waste management. However, the reason about

choosing AR technologies compare to others will be discussed further in literature review chapter. It followed by the proposed methodology, result and discussion, and conclusion and future work in each chapter respectively.

II. Literature Review

In this research, Augmented Reality (AR) technology was chosen because AR brings the 3D world into the real world, transforming the dimensions of learning becoming more realistic and enhancing brain productivity [36]. Additionally, AR provides and effective solution in the learning process [37] and according to literature studies [38] it can be concluded that AR has a positive contribution to learning outcomes in children. Research in study [39] found that AR application able to help children to gain their memory about places that located in playmate and spell it easily. Other studies [40] shows the comparison in group of students between AR based application, Video based, and traditional teaching method. The outcome of the study concludes that AR based outweighs the other two methods in terms of learning achievement through some quizzes in the class. Study about AR also discussed in study [41], it found that some volunteers said that AR technology help them increasing their willingness to study the book, even outside the class.

Beside AR, several studies also describe the importance of the presence of gamification elements in learning mobile application. Firstly, the development of 2D puzzle game application [42] successfully transform learning into an engaging learning environment and educated student on proper waste sorting methods. It contains several gamification concepts, including scoring, and level. Secondly, another study [43] developed a 2D waste sorting game that divided trash into two types, are organist and inorganic. The research built in Unity3D and used gamification elements, namely: level, score, time limit, reward, and level. Another study in study [43] that use gamification standards also gives positives feedback from the user. It stated that above 80% said that thorough the application it helps user to understand more about the material. According to its successfulness of contributions from users. Therefore, this research also takes the gamification into consideration while design an AR sorting waste application.

Study about Mixed Reality (MR) including Virtual Reality (VR) and AR about environment and waste sortation already conducted. One of the studies about VR game related to waste sorting called “KEEPIN” also categorized waste into two types, organic and inorganic, the main subject of the application are children between aged 7-12 years [44]. The results of the study indicated that the majority children responded positively to the game and were able to complete the challenges successfully. AR has also been developed by study [45] to recycle existing waste by scanning barcodes. Mini games of recycling using AR has been discussed in study [46], it categorizes waste into three types, are: organic, non-organic, and electronic. Besides that, it also includes reward point for every correct answer. The outcome result of the experiment shows that user gain knowledge and improve their attitudes about climate change issue according to material presented in AR mobile. According to the discussion on several topics about waste sortation, it can be concluded that, mostly there are two and three types of garbage bin in mobile application development.

Complementing other studies related to waste, the novelty of this research is to create an AR application that categorizes waste into seven types: organic waste, paper waste, electronic waste, hazardous and toxic waste, plastic waste, metal waste, and residual waste [47]. Additionally, the educational technology using AR in this study has a wider user reach because it can be used not only for children but also for adult.

However, the gamification function in this study is focused on children starting at the age of seven because children can more effectively transfer their knowledge to other family members [23]. Moreover, the introduction of new information related to waste types will be more effective if introduced from an early age [43]. According to study [48], children at the age of seven are already able to use simple AR applications, making this technology relevant for children.

According to some papers that conduct AR research, it can be summarized that VR and AR application for waste sorting that contains gamification elements show positive results. However, the types of waste that has been developed not complete enough. Therefore, this research aims to develop an AR application that divide waste into seven types. In terms of subject target, this research focus on children based on their ability to transfer knowledge within their family and relatives. Besides that, it also relevant with their receptiveness to AR technology.

III. Methodology

This research uses ADDIE (Analysis, Design, Development, Implementation, and Evaluation) development model. This method was chosen because based on [49] ADDIE is the recommended method that uses in educational or training application which able for independent learning. ADDIE model which used in this research presented in Fig. 1. The model generally has three main process, are pre-production, production, and post-production.

A. Analysis

In the pre-production process, a needs analysis was carried out by identifying types of waste in seven categories which were discussed in the literature review to be implemented in the AR application using literature studies. Apart from that, interviews with users were also carried out, and the types of waste that were often found in the surrounding environment were obtained, as well as children's ability to operate smartphones.

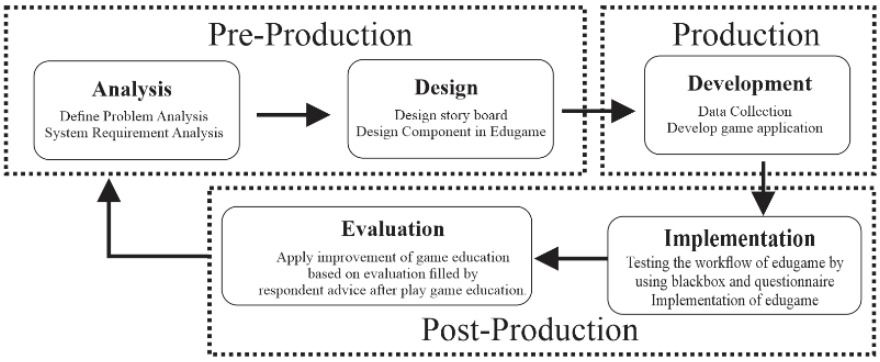

Fig. 1. ADDIE research method.

B. Design

Design process becoming the second stage that need to be done based on ADDIE development. In design of AR application, it considered important to have six basics elements [50], namely: application users, AR interactions, devices, servers, virtual and real content, as well as the process of moving between screens that runs well and smoothly. In the AR technology design process, researchers used CCI (Child-Computer Interaction) standards and gamification elements including: scoring system, sound, level, animation, large picture, and button. This standard is quite important to implement, because it combines learning concepts in the mobile application design process [48]. Further implementation about design application can be seen in Section IV.

C. Development

In the production stage, AR technology mainly was developed using Unity3D software of game development that important to build an interactive interface and experience of VR and AR. Besides that, Vuforia SDK also implemented to perform AR package that connected with Unit3D. Vuforia SDK was chosen based on its ability to recognize markers on all types of objects which other platforms do not have [51]. Other tools are: Playmaker visual scripting, and Visual Studio (C#) that useful to perform scripting code in Unity3D. In this research, blender software also used to perform modelling 3D and adding animation movement in 3D object. Detail workflow in the AR development process presented in Fig. 2.

Based on the AR Development process in Fig. 2, describes the process of detecting AR started with the smartphone device capture the marker using camera. After that, Vuforia SDK that equipped with AR camera try to find similar marker in database that already uploaded in vuforia website. In this research image target marker that used local database (database stored in device) has been used. Vuforia SDK will analyse and find similarities between image and features in marker. Whenever the marker able to detect through devices the render view has been sent to the application and display in user mobile application. The virtual button option also appeared that useful to perform many actions based on logic programming that has been written using C# or Playmaker visual scripting.

The building process of application in APK and AAB extensions requires some customization, including: need to equipped ARM 64, using target API level 33 on android system, and it is necessary setting several input systems on build setting. Complete explanation about build setting discussed further in Section IV.

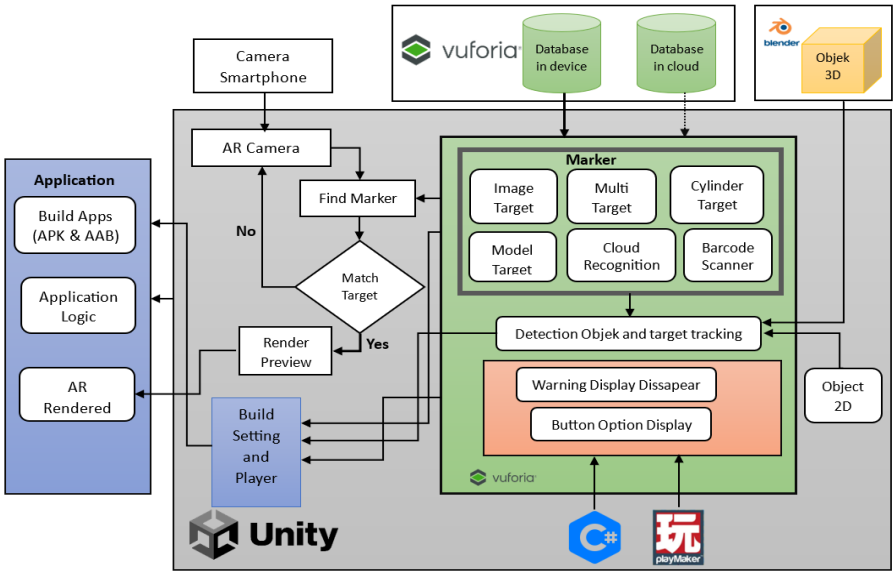

Fig. 2. AR development process.

D. Implementation

In the implementation steps, before application deliver to the users, it considers necessary to apply several testing methods to ensure the application run without any error and accepted by users. Therefore, in this research used blackbox and System Usabiliy Scale (SUS) testing. The first testing has been chosen because its effectiveness and it became one of fungsional testing that gives accurate result [5][52]. While the latter carried out during testing process, because it used to determine the acceptance rate and usability of the system according to users [6], [7] [53], [54]. SUS method has been used despite other testing because it is one of the most test carried out for testing the usability of system and still relevant nowadays [6] [53]. SUS question in this research can be seen in Table I. It uses the original list of question that published by [7] [54]. However, to make it relevant baes on this study the question already undergone slight modification. The scoring scale in SUS used five degrees of scoring, that start from 1 (strongly disagree) to 5 (strongly agree) [8] [55].

TABLE I. LIST OF SUS QUESTIONNAIRE

No	List of Question
1	I think that I would like to use this application frequently
2	I found the application unnecessarily complex
3	I thought the application was easy to use
4	I think that I would need the support of a technical person to be able to use this application
5	I found the various functions in this application were well integrated.
6	I thought there was too much inconsistency in this application
7	I would imagine that most people would learn to use this application very quickly.
8	I found the application very cumbersome to use
9	I felt very confident using the application
10	I needed to learn a lot of things before I could get going with this application

E. Evaluation

This stage becoming important because it use to improve AR technology based on recommendation from users. After that the next stage start from the beginning again. It can be seen in Fig. 1 that ADDIE method not run only in one phase, it is an iteration process. Therefore, the application will become better in every phase.

IV. RESULTS AND DISCUSSION

According to research method described in section three, this AR application was made for children start from seven years old. This decision has been made based on discussion on literature review and interview from user. Some tools that used in this research discussed in chapter three already imported in Unity3D. The overview of the project design can be seen in Fig. 3 and Fig. 4.

According to Fig. 3, shows that CCI elements need to be inputted in AR application as discuss in chapter three in design method. Therefore, it already implemented in main menu, such as: large picture and button, sound in the application, and animation that already made in Unity3D using animation and animator tab. Fig. 4 describe the menu of AR in application that mainly used Vuforia SDK which used for implementing augmented reality that already discussed in chapter three. It can be seen from Fig. 4, that AR menu requires AR camera that useful to scanning marker and match the marker captured by AR with database in devices.

Some configurations for controlling object and events that appears and disappears in AR menu when marker match with database already described in Fig. 5. This is useful to prevent unwanted objects appear unexpectedly.

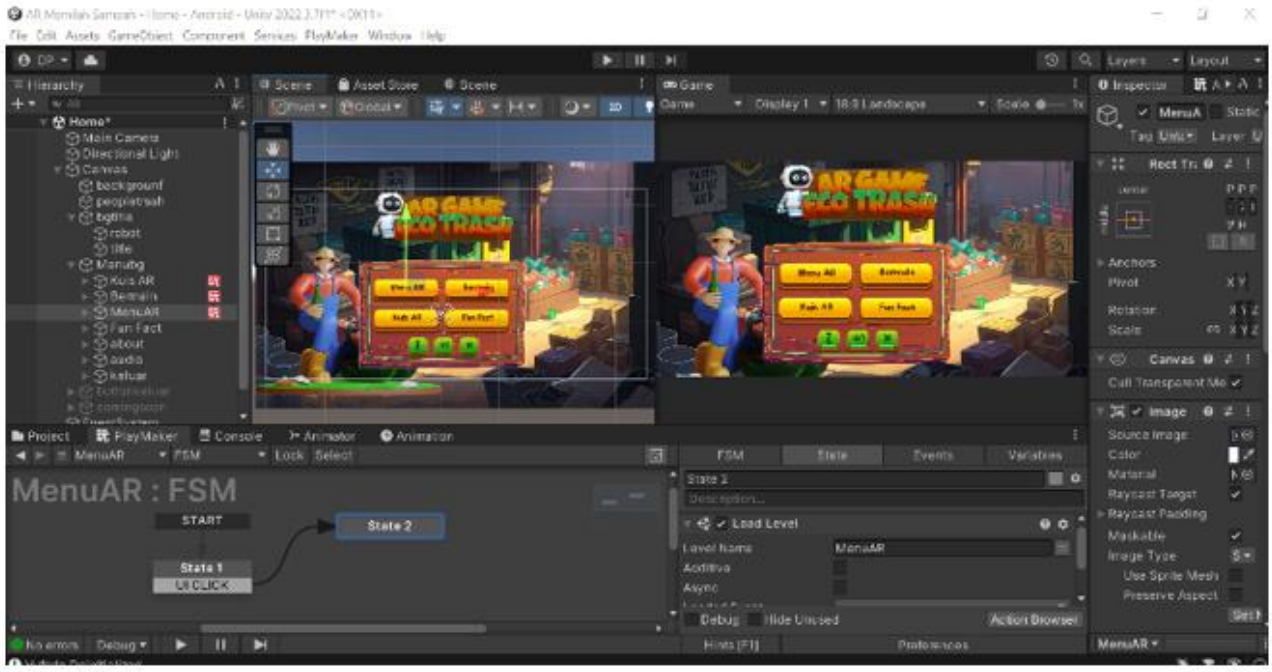

Fig. 3. Main menu in Unity3D.

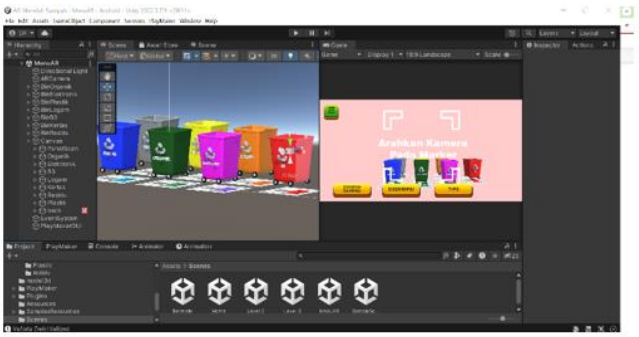

Fig. 4. AR menu in unity3D.

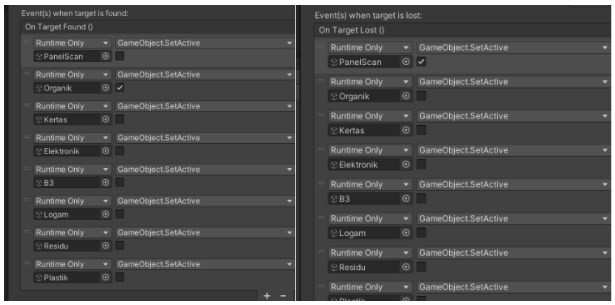

Fig. 5. Event when target found and lost.

According to Fig. 4, it can be assumed that whenever the target found it will display bin "organik" object, while others object will remain unactive. Otherwise, when the target lost it will display "panelscan" that contain instruction command to capture marker that available using camera. The snipped code to control game object which active or not whenever the button pressed can be seen in Fig. 6.

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using UnityEngine.UI;

public class OnOff : MonoBehaviour
{
    public GameObject objek;

    public void whenButtonClicked()
    {
        if(objek.activeInHierarchy == true)
        objek.SetActive(false);
        else
        objek.SetActive(true);

    }
}
```

Fig. 6. On-off button display.

Beside AR menu, this application also has quiz menu that divided into AR Quiz and Drag and drop quiz that presented in Fig. 7 and Fig. 8. The design of quiz menu also follows CCI elements that has level of game, scoring system, and simple challenge.

In AR Quiz menu, it will detect the correct answer by searching the same name from the multiple choice presented and game object that active. According to Fig. 8, there are 18 questions and the score point will be added in the right top corner of the screen. The snippet code about scoring system and correct answer can be seen in Fig. 9.

Fig. 7. Drag and drop quiz.

Fig. 8. AR quiz menu.

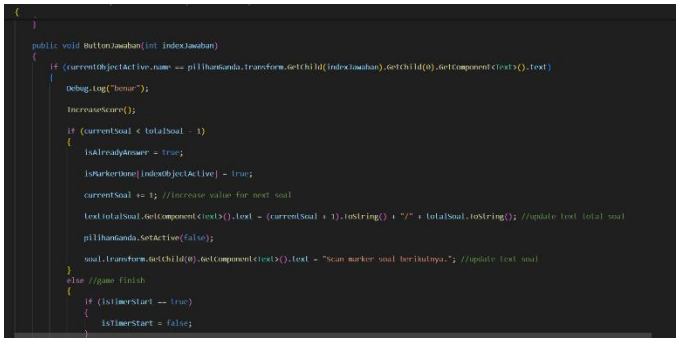

Fig. 9. Snipped code for AR quiz.

After the development process are finished, it is necessary to perform blackbox testing to prevent error and make sure that every function in application run as expected. The result of blackbox testing for this application presented in Table II.

After buildbox testing run successfully without any errors, the SUS questionnaire then conducted to make sure that application can be useful and easy for user to play. The score and answer based on SUS questionnaire that already presented in Table I can be seen in Table III.

According to table three, the average score of obtain 84,5 that based on Fig. 10 lies on "good" area and the application already acceptable for users.

Based on result of SUS in Table III, it can be seen, that the lowest score about 70 that still in a "good" area. Therefore, it can be concluded this AR application already acceptable to be used for end user.

TABLE II. BLACKBOX TESTING

No	Test Class	Scenario Testing	Expected	Result
	Menu AR	Pressing Menu AR Button	Display Menu AR and if marker capture displayed Object 3D and three options: contoh sampah, deskripsi, tips	Valid
	Contoh Sampah	Pressing Contoh Sampah Button	Display several items garbage in seven categories based on marker that capture	Valid
	Deksripsi	Pressing deskripsi Button	Display description of garbage that belongs in each category based on marker that capture	Valid
	Tips	Pressing Tips Button	Display tips to reduce garbage that belongs in each category based on marker that capture	Valid
	Bermain	Pressing Bermain Button	Display bermain menu that allows user drag garbage and drop it in each bin	Valid
	Level 1 in Bermain Menu	Finished level 1	Display level 1 of bermain menu which consists of four types of garbage and four times to play	Valid
	Level 2 in Bermain Menu	Finished level 2	Display level 2 of bermain menu which consists of five types of garbage and three times to play	Valid
	Level 3 in Bermain Menu	Finished level 3	Display level 3 of bermain menu which consists of six types of garbage and three times to play	Valid
	Kuis AR	Pressing Kuis AR Button	Display Kuis AR that allow user to answer the question by capturing marker	Valid
	Fun Fact	Pressing Fun Fact Button	Display fun fact menu about sorting waste	Valid
	Exit	Pressing Exit Button	Display exit menu which allows user to exit from application	Valid
	Sound	Pressing Sound Button	Enable and disable sound form application	Valid
	About	Pressing About Button	Display information about application	Valid

TABLE III. RESULT OF SUS QUESTIONNAIRE

User	Score										Sum Score * 2.5
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	
1	3	3	3	3	4	2	3	3	3	2	72,5
2	3	4	4	1	4	4	4	4	4	2	85
3	2	4	3	4	3	4	4	4	4	4	90
4	3	3	3	4	4	3	3	3	4	3	82,5
5	4	4	4	4	3	4	2	4	2	4	87,5
6	3	3	3	4	3	3	3	4	3	3	80
7	3	4	3	1	4	3	4	3	3	1	72,5
8	4	4	4	4	3	3	4	4	4	3	93
9	3	3	3	3	4	3	4	3	3	3	80
10	1	4	3	3	4	4	3	4	4	2	80
11	4	4	4	4	4	4	4	4	4	2	95
12	2	1	3	3	3	3	3	4	2	4	70
13	3	3	3	4	3	4	3	4	4	3	85
14	4	4	4	4	4	4	4	4	4	2	95
15	4	3	3	3	4	4	3	4	4	3	88
16	4	3	3	4	3	4	4	3	2	1	78
17	4	3	4	3	3	4	3	3	4	2	83
18	4	2	3	4	4	4	4	3	3	4	87,5
19	3	4	4	1	4	4	4	4	4	2	85
20	4	4	4	4	4	4	4	4	4	3	97,5
21	2	1	3	3	3	3	3	4	2	4	70
22	4	4	4	4	3	4	2	4	2	4	87,5
23	3	2	3	1	4	2	2	3	4	1	62,5
24	4	2	3	4	4	4	4	3	3	4	87,5
25	4	3	3	3	4	4	3	4	4	3	88
26	4	3	4	3	4	4	3	4	4	3	90
27	3	4	4	1	4	4	4	4	4	2	85
28	4	4	4	4	4	4	4	4	4	3	97,5
29	4	4	4	4	4	4	4	3	4	4	97,5
30	3	3	3	4	3	4	3	4	4	3	85
Average Score											84,5

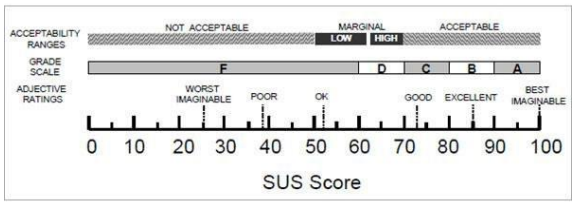

Fig. 10. Range of SUS score.

V. Conclusion and Future Work

Based on the result obtain in chapter four, it can be assumed that the objective of this research was successfully achieved, as evidence by the development and implementation of AR garbage sortation on mobile application. Besides that, the use of AR technology has proven to be effective in creating and engaging and interactive learning environment. The AR application able to transform types of waste into visual experience by combine the virtual and real world. This visualization making it easier for children to understand and remember the different types of waste.

According to the user acceptance, it concludes that the application received positive feedbacks. It can be seen based on the average score that obtain average of 84.5 out of 100 that lies on "good" category. It is indicated that the application accepted and consider user friendly by users. All in all, the novelty of this research lies on its comprehensive categories of waste into seven types, which more detailed compared to previous studies. Additionally, the integration of AR technology alongside with gamification elements enhances users learning experience. Therefore, the used not only enlarge their knowledge but also able to enjoy the application.

Despite its successfulness, this application has many works to do in the future, including addition of types of waste, and fun fact. Besides that, the knowledge effect of this AR application needs to be tested as well. Furthermore, the extension of education content also considers important for the future improvements.

Acknowledgment

The authors would like to express their sincere gratitude to UMS and RisetMu for their invaluable support esepecially for research grant. This research is fully funded by Riset Muhammadiyah (RisetMu) Majelis Pendidikan Tinggi Penelitian dan Pengembangan Pimpinan Pusat Muhammadiyah under the grant number 0258.039/I.3/D/2024.

References

[1] L. M. Hunter, A. Hatch, and A. Johnson, "Cross-National Gender Variation in Environmental Behaviors *," *Soc Sci Q*, vol. 85, no. 3, pp. 677–694, Sep. 2004, doi: 10.1111/j.0038-4941.2004.00239.x.

[2] E. N. S. Alkhajar and A. R. Luthfia, "Daur Ulang Sampah Plastik Sebagai Mitigasi Perubahan Iklim," *Jurnal Penamas Adi Buana*, vol. 4, no. 1, pp. 61–64, Jul. 2020, doi: 10.36456/penamas.vol4.no1.a2524.

[3] U. Lee, J. Han, and M. Wang, "Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways," *J Clean Prod*, vol. 166, pp. 335–342, Nov. 2017, doi: 10.1016/j.jclepro.2017.08.016.

[4] P. O. Njoku and J. N. Edokpayi, "Estimation of landfill gas production and potential utilization in a South Africa landfill," *J Air Waste Manage Assoc*, vol. 73, no. 1, pp. 1–14, Jan. 2023, doi: 10.1080/10962247.2022.2072976.

[5] C. Zhang, Y. Guo, X. Wang, and S. Chen, "Temporal and spatial variation of greenhouse gas emissions from a limited-controlled landfill site," *Environ Int*, vol. 127, pp. 387–394, Jun. 2019, doi: 10.1016/j.envint.2019.03.052.

[6] G. Allen *et al.*, "The development and trial of an unmanned aerial system for the measurement of methane flux from landfill and greenhouse gas emission hotspots," *Waste Management*, vol. 87, pp. 883–892, Mar. 2019, doi: 10.1016/j.wasman.2017.12.024.

[7] L. Morganti, F. Pallavicini, E. Cadel, A. Candelieri, F. Archetti, and F. Mantovani, "Gaming for Earth: Serious games and gamification to engage consumers in pro-environmental behaviours for energy efficiency," *Energy Res Soc Sci*, vol. 29, pp. 95–102, Jul. 2017, doi: 10.1016/j.erss.2017.05.001.

[8] A. A. de Souza Machado, W. Kloas, C. Zarfl, S. Hempel, and M. C. Rillig, "Microplastics as an emerging threat to terrestrial ecosystems," *Glob Chang Biol*, vol. 24, no. 4, pp. 1405–1416, Apr. 2018, doi: 10.1111/gcb.14020.

[9] E. M. Bennett and P. Alexandridis, "Informing the Public and Educating Students on Plastic Recycling," *Recycling*, vol. 6, no. 4, p. 69, Oct. 2021, doi: 10.3390/recycling6040069.

[10] J. R. Jambeck *et al.*, "Plastic waste inputs from land into the ocean," *Science (1979)*, vol. 347, no. 6223, pp. 768–771, Feb. 2015, doi: 10.1126/science.1260352.

[11] R. Geyer, J. R. Jambeck, and K. L. Law, "Production, use, and fate of all plastics ever made," *Sci Adv*, vol. 3, no. 7, Jul. 2017, doi: 10.1126/sciadv.1700782.

[12] O. Gaggi, F. Meneghello, C. E. Palazzi, and G. Pante, "Learning how to recycle waste using a game," in *Proceedings of the 6th EAI International Conference on Smart Objects and Technologies for Social Good*, New York, NY, USA: ACM, Sep. 2020, pp. 144–149. doi: 10.1145/3411170.3411251.

[13] C. Adam, "Perancangan Poster Augmented reality Dampak Sampah Plastik bagi Lingkungan," *Nirmana*, vol. 23, no. 1, pp. 59–66, Feb. 2023, doi: 10.9744/nirmana.23.1.59-66.

[14] C. Meidiana and T. Gamse, "Development of Waste Management Practices in Indonesia," 2010. [Online]. Available: http://www.eurojournals.com/ejsr.htm

[15] Kardono, "Integrated Solid Waste Management in Indonesia," *Integrated solid waste management in Indonesia Proc. International Symposium on EcoTopia Science*, pp. 629–633, 2007.

[16] B. Pradere *et al.*, "Climate-smart Actions in the Operating Theatre for Improving Sustainability Practices: A Systematic Review," *Eur Urol*, vol. 83, no. 4, pp. 331–342, Apr. 2023, doi: 10.1016/j.eururo.2022.01.027.

[17] K. H. Wyssusek, W. M. Foong, C. Steel, and B. M. Gillespie, "The Gold in Garbage: Implementing a Waste Segregation and Recycling Initiative," *AORN J*, vol. 103, no. 3, Mar. 2016, doi: 10.1016/j.aorn.2016.01.014.

[18] R. J. Lee and S. C. Mears, "Greening of Orthopedic Surgery," *Orthopedics*, vol. 35, no. 6, Jun. 2012, doi: 10.3928/01477447-20120525-39.

[19] L. T. Nindyapratama and H. A. Ahmad, "The Potential of Adventure Game as a Media to Visualize Waste Disposal as Environmental Problems," 2021. doi: 10.2991/assehr.k.211228.020.

[20] Mikael Niman, "Pengolahan TPST Bantargebang Dinilai Makin Baik," https://www.beritasatu.com/megapolitan/729677/pengolahan-tpst-bantargebang-dinilai-makin-baik.

[21] Tim Publikasi Katadata, "Kesadaran Warga Memilah Sampah Masih Rendah," https://katadata.co.id/berita/nasional/5e9a470c74665/kesadaran-warga-memilah-sampah-masih-rendah.

[22] S. Azouz, P. Boyll, M. Swanson, N. Castel, T. Maffi, and A. M. Rebecca, "Managing barriers to recycling in the operating room," *The American Journal of Surgery*, vol. 217, no. 4, pp. 634–638, Apr. 2019, doi: 10.1016/j.amjsurg.2018.06.020.

[23] R. Bardhan, C. Bahuman, I. Pathan, and K. Ramamritham, "Designing a game based persuasive technology to promote pro-environmental behaviour (PEB)," in *2015 IEEE Region 10 Humanitarian Technology*

Conference (R10-HTC), IEEE, Dec. 2015, pp. 1–8. doi: 10.1109/R10-HTC.2015.7391844.

[24] A. Nair, A. Nair, R. Shetty, S. Samant, and S. Agrawal, "Analyzing User Requirements and Interface Designing on Mobile Solutions for Waste Segregation," in *2021 6th International Conference for Convergence in Technology (I2CT)*, IEEE, Apr. 2021, pp. 1–8. doi: 10.1109/I2CT51068.2021.9417873.

[25] M. Kalz, D. Börner, S. Ternier, and M. Specht, "Mindergie: A Pervasive Learning Game for Pro-environmental Behaviour at the Workplace," in *Seamless Learning in the Age of Mobile Connectivity*, Singapore: Springer Singapore, 2015, pp. 397–417. doi: 10.1007/978-981-287-113-8_20.

[26] B. J. Fogg, "Persuasive technology," *Ubiquity*, vol. 2002, no. December, p. 2, Dec. 2002, doi: 10.1145/764008.763957.

[27] C. A. Anderson and B. J. Bushman, "Effects of Violent Video Games on Aggressive Behavior, Aggressive Cognition, Aggressive Affect, Physiological Arousal, and Prosocial Behavior: A Meta-Analytic Review of the Scientific Literature," *Psychol Sci*, vol. 12, no. 5, pp. 353–359, Sep. 2001, doi: 10.1111/1467-9280.00366.

[28] S. M. Ogletree and R. Drake, "College Students' Video Game Participation and Perceptions: Gender Differences and Implications," *Sex Roles*, vol. 56, no. 7–8, pp. 537–542, Apr. 2007, doi: 10.1007/s11199-007-9193-5.

[29] M. D. Griffiths, M. N. O. Davies, and D. Chappell, "Online computer gaming: a comparison of adolescent and adult gamers," *J Adolesc*, vol. 27, no. 1, pp. 87–96, Feb. 2004, doi: 10.1016/j.adolescence.2003.10.007.

[30] J. K. Mullins and R. Sabherwal, "Beyond Enjoyment: A Cognitive-Emotional Perspective of Gamification," in *Proceedings of the 51st Hawaii International Conference on System Sciences* |, 2018, pp. 1237–1246. [Online]. Available: http://hdl.handle.net/10125/50039

[31] D. Gibovic and A. Bikfalvi, "Incentives for Plastic Recycling: How to Engage Citizens in Active Collection. Empirical Evidence from Spain," *Recycling*, vol. 6, no. 2, p. 29, Apr. 2021, doi: 10.3390/recycling6020029.

[32] Z. Zainuddin, S. K. W. Chu, M. Shujahat, and C. J. Perera, "The impact of gamification on learning and instruction: A systematic review of empirical evidence," *Educ Res Rev*, vol. 30, p. 100326, Jun. 2020, doi: 10.1016/j.edurev.2020.100326.

[33] D. A. Mawsally and E. Sudarmilah, "A Virtual-Reality Edu-Game: Save The Environment from the Dangers of Pollution," *Khazanah Informatika : Jurnal Ilmu Komputer dan Informatika*, vol. 5, no. 2, pp. 140–145, Dec. 2019, doi: 10.23917/khif.v5i2.8194.

[34] Hasna Azizah and Fatah Yasin Irsyadi, "Educational Game in Learning Arabic Language for Modern Islamic Boarding School," *Jurnal RESTI (Rekayasa Sistem dan Teknologi Informasi)*, vol. 4, no. 3, pp. 489–496, Jun. 2020, doi: 10.29207/resti.v4i3.1894.

[35] R. Nuqisari and E. Sudarmilah, "Pembuatan Game Edukasi Tata Surya dengan Construct 2 Berbasis Android," *Jurnal Teknik Elektro*, vol. 19, no. 02, 2019.

[36] M. Aborokbah, "Using augmented reality to support children with dyslexia," *International Journal of Cloud Computing*, vol. 10, no. 1/2, p. 17, 2021, doi: 10.1504/IJCC.2021.113972.

[37] R. Clemens, S. Purcell, and D. Slykhuis, "Implementing Augmented Reality in K-12 Education – Analyzing Current trends," in *Society for Information Technology & Teacher Education International Conference*, Savannah, GA, United States: Association for the Advancement of Computing in Education (AACE), 2016, pp. 1960–1967.

[38] J. Garzón and J. Acevedo, "Meta-analysis of the impact of Augmented Reality on students' learning gains," *Educ Res Rev*, vol. 27, pp. 244–260, Jun. 2019, doi: 10.1016/j.edurev.2019.04.001.

[39] S. A. Hassan, T. Rahim, and S. Y. Shin, "ChildAR: an augmented reality-based interactive game for assisting children in their education," *Univers Access Inf Soc*, vol. 21, no. 2, pp. 545–556, Jun. 2022, doi: 10.1007/s10209-020-00790-z.

[40] Afnan, K. Muhammad, N. Khan, M.-Y. Lee, A. Imran, and M. Sajjad, "School of the Future: A Comprehensive Study on the Effectiveness of Augmented Reality as a Tool for Primary School Children's Education," *Applied Sciences*, vol. 11, no. 11, p. 5277, Jun. 2021, doi: 10.3390/app11115277.

[41] S.-Y. Chen, "To explore the impact of augmented reality digital picture books in environmental education courses on environmental attitudes and environmental behaviors of children from different cultures," *Front Psychol*, vol. 13, Dec. 2022, doi: 10.3389/fpsyg.2022.1063659.

[42] M. C. G. Fernando, M. B. Garcia, M. V. Solomo, and A. Lagman, "Trash Attack: A 2D Action Puzzle Video Game to Promote Environmental Awareness and Waste Segregation Behavior," *International journal of simulation: systems, science & technology*, Jul. 2019, doi: 10.5013/IJSSST.a.20.S2.24.

[43] H. Rahmayanti, V. Oktaviani, and Y. Syani, "Development of sorting waste game android based for early childhood in environmental education," *J Phys Conf Ser*, vol. 1434, no. 1, p. 012029, Jan. 2020, doi: 10.1088/1742-6596/1434/1/012029.

[44] R. Maharani Putri Siregar, E. Sudarmilah, and Istiadi, "Approachability Evaluation of Virtual Reality Educational Game: The Case of Keepin," *J Phys Conf Ser*, vol. 1908, no. 1, p. 012013, Jun. 2021, doi: 10.1088/1742-6596/1908/1/012013.

[45] A. Vikiru, S. Mujera, and K. Kangethe, "Waste Management using Augmented Reality," 2019. doi: 10.13140/RG.2.2.14780.16009.

[46] K. Wang, Z. D. Tekler, L. Cheah, D. Herremans, and L. Blessing, "Evaluating the Effectiveness of an Augmented Reality Game Promoting Environmental Action," *Sustainability*, vol. 13, no. 24, p. 13912, Dec. 2021, doi: 10.3390/su132413912.

[47] DKI Jakarta (Provinsi), "Instruksi Gubernur Nomor 107 Tahun 2019 tentang Pengurangan dan Pemilahan Sampah diLingkungan Pemerintah Provinsi Daerah Khusus Ibukota Jakarta." Accessed: Feb. 10, 2024. [Online]. Available: https://jdih.jakarta.go.id/dokumen/detail/3771

[48] B. Haznedar, "Child second language acquisition from a generative perspective," *Linguist Approaches Biling*, vol. 3, no. 1, pp. 26–47, Mar. 2013, doi: 10.1075/lab.3.1.02haz.

[49] G. Muruganantham, "Developing of E-content package by using ADDIE model," *International Journal of Applied Research*, vol. 1, no. 3, pp. 52–54, 2015, [Online]. Available: www.allresearchjournal.com

[50] S. Liang, "Design Principles of Augmented Reality Focusing on the Ageing Population," in *30th International BCS Human Computer Interaction Conference*, 2016. doi: 10.14236/ewic/HCI2016.2.

[51] Suzanna, Sasmoko, F. L. Gaol, and T. Oktavia, "Augmented Reality SDK Overview for General Application Use," *International Journal of Advanced Computer Science and Applications*, vol. 14, no. 11, 2023, doi: 10.14569/IJACSA.2023.0141106.

[52] K. Hrisafov, A. B. Ivanov, N. Chivarov, and S. Chivarov, "Black Box Testing with Exploratory Approach of a Software for Remote Monitoring of Patients with COVID-19 and Other Infectious Diseases," in *2021 International Conference on Electrical, Computer and Energy Technologies (ICECET)*, IEEE, Dec. 2021, pp. 1–5. doi: 10.1109/ICECET52533.2021.9698734.

[53] J. R. Lewis, "The System Usability Scale: Past, Present, and Future," *Int J Hum Comput Interact*, vol. 34, no. 7, pp. 577–590, Jul. 2018, doi: 10.1080/10447318.2018.1455307.

[54] S. K. Brooks *et al.*, "The psychological impact of quarantine and how to reduce it: rapid review of the evidence," *The Lancet*, vol. 395, no. 10227, pp. 912–920, Mar. 2020, doi: 10.1016/S0140-6736(20)30460-8.

[55] A. Kaya, R. Ozturk, and C. Altin Gumussoy, "Usability Measurement of Mobile Applications with System Usability Scale (SUS)," 2019, pp. 389–400. doi: 10.1007/978-3-030-03317-0_32.