Original Research Paper

AR Technology Educational Game for Inspiring Students to Implement Zero Waste Management

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Abstract: Alongside Malaysia's population expansion, the amount of waste being thrown away has continuously increased, with the majority of it ending up in landfills. AR bridges the gap between abstract ideas and real-world experiences by allowing students to see and interact with virtual objects and information in the actual world. 5Rs-AG (AR Technology Educational Game for Inspiring Students to Implement Zero Waste Management) app is a mobile application that has AR technology in it to assist target users like students, local communities also UPSI students to learn and as for teachers to use as a learning aid in the learning process in school. The objective of this research is to identify significant elements of creating an effective learning aid by developing an AR mobile game about the 5Rs of zero waste management, develop the prototype in the mobile application AR Game also evaluate the usability of the developed prototype AR Game. The method that is being used is the Evolutionary Prototyping model. The evaluation is conducted using the System Usability Scale (SUS). Random 18 respondents are participated answering the Evaluation Form. From the analysis finding, the mean from all the statements is 3.84 which represents all the respondents are Agree and the SUS Final Score is 71.35 that represents as Good. Thus, using AR technology is the best way for students to learn interactively about waste management.

Keywords: 5Rs Concept, Augmented Reality (AR), Educational Game, Mobile Application, Zero Waste Management.

1. Introduction

The global spread of technology over the past several years has brought about a lot of changes in a variety of industries, including entertainment and education. In general, technology aids in the simplification and ease of all jobs. The use of Augmented Reality (AR), which transforms how we interact with digital information and improves our physical environment, has become a common technology in a variety of fields. AR describes the incorporation of digital content into the actual world, such as the overlaying of information or virtual objects, to enhance our perception and create an immersive user experience.

The solid waste in Malaysia has increased along with the tremendous population urbanization and economic growth [1] [2]. For the sake of the environment, the preservation of resources, and public health, effective waste management is essential. In Malaysia, the terms we use for 5Rs waste management are Reduce, Reuse, Recycle, Rethink/Refuse, and Repair/Repropose. Learning about the 5Rs of zero waste management has already been put in today's education to give prior knowledge to students in schools as 5Rs zero waste management has been introduced in Moral Textbook Form 3.

Learning the 5Rs of waste management is important because we can get several benefits from it. First, in terms of environmental consciousness, students who are taught about the 5Rs can develop an early sense of environmental responsibility [3] [4] [5]. They gain knowledge about how garbage affects the ecosystem and comprehend the significance of choosing sustainable options. In order to reduce waste issues management, a suitable platform needs to be built to spread information and news about the importance of zero waste management and all of it can start in education at school.

The use of Augmented Reality (AR) technology in education has attracted a lot of interest and is being introduced into classrooms more frequently [6]. AR technology can have a positive impact on students because we can enhance engagement and interactivity during the teaching and learning process. Through interactive and immersive experiences, AR brings learning to life [7], incorporating AR into scientific courses can improve students' learning while also improving their knowledge and academic achievement.

The availability of AR mobile applications, however, that deliver the most recent details on the 5Rs zero waste management idea, seems to be lacking. The existing mobile game does not provide info or general information about the 5Rs zero waste management. So, a platform needs to be created where students can learn about waste management while playing the game. When students engage in a game, their motivation increases, leading to better participation and the ability to form connections and positive memories of learning [8] [9].

The specialty in AR mobile apps is students can learn and improve their knowledge while playing the game. AR bridges the gap between abstract ideas and real-world experiences by allowing students to see and interact with virtual objects and information in the actual world. All the contents like awareness and info related to zero waste management need to be included in the mobile app so that can the user know and have the knowledge about it and practice it in their daily life. The main is on students because the purpose developed this AR mobile application is to make sure students understand the importance of saving our Earth by learning about waste management [10].

The objective of this research is as follows: to identify the significant elements of creating an effective learning aid by developing an AR mobile game about the 5Rs of zero waste management, to develop the prototype in the mobile application AR Game, and to evaluate the usability of the developed prototype mobile application AR- Game.

2. Literature Review

2.1. Moral Education

In Malaysia, Moral Education refers to educational programmes designed to impart moral principles, ethical behaviour, and character development. The inclusion of moral studies in the national curriculum reflects its importance as a crucial component of the educational system. Spiritual and moral education serves as a measure of an individual's ability to improve their morality by assimilating the spiritual and intellectual benefits of society [11] [12].

Beyond academic knowledge, this subject emphasizes the development of empathy and responsible behaviour. Ethical values such as honesty, integrity, respect, and kindness are foundational to the holistic development of individuals. By establishing these principles at an early age, a more perceptive and peaceful society can be achieved [13].

One effective pedagogical approach to teaching character education is storytelling. Based on the concepts of the Zone of Proximal Development (ZPD) and scaffolding, moral development occurs as children internalize values through listening and reading. This process helps students gradually adopt moral values as daily habits [14].

Moral Education addresses contemporary social issues, including environmental concerns and social justice. This awareness helps students develop empathy toward global challenges. Conceptually, moral, character, and citizenship education are interrelated, as citizens must uphold societal standards through the excellent character developed in school [15] [16].

The curriculum is regularly updated to ensure its relevance in nurturing ethical development. Teachers play a pivotal role as role models and guides in this process. Ultimately, Moral Education sets the groundwork for a morally upright populace, encouraging harmony among various communities in Malaysia.

2.2. 5Rs Zero Waste Management

Waste management involves the systematic collection, transportation, processing, and monitoring of various waste items. This process is crucial to protect the environment from the harmful impacts of inorganic and biodegradable materials. Improper management can lead to water poisoning, soil erosion, and air pollution; however, effective handling allows waste to be recycled into new goods, thereby conserving natural resources.

According to the World Wildlife Fund (WWF), an estimated 8 million tonnes of plastic enter the oceans annually. Efficient waste management not only preserves biodiversity but also benefits the economy by creating jobs in the recycling industry. Over time, it has evolved from a matter of environmental protection into a growing economic sector [17].

The 5Rs framework “Reuse, Reduce, Recycle, Rethink, and Repair” was introduced to help individuals manage waste more efficiently. "Reduce" focuses on minimizing harmful and non-recyclable materials to benefit both the environment and finances. "Reuse" encourages the responsible use of materials to lower the global volume of trash [18].

Recycling is recognized as a highly environmentally friendly waste disposal method [18]. Beyond common recyclables like glass and plastic, the concept of "Rethink" (as seen in the Moral Education Form 3 syllabus) encourages users to consider the environmental impact of items, such as electronics, before disposal.

The final component, "Repair," involves fixing damaged items to extend their lifespan and reduce landfill waste. Effective waste management is essential for reducing greenhouse gas emissions and protecting ecosystems. It plays a significant role in maintaining a clean and healthy living environment for all communities [19].

2.3. The Use of Technologies Related to 5Rs Zero Waste Management

Current technological innovations, such as the Internet of Things (IoT) and Artificial Intelligence (AI), are significantly easing waste management operations. these advanced technologies boost efficiency, reduce costs, and enable better decision-making for a sustainable future.

AI-driven systems now utilize sensors and algorithms to capture and classify garbage automatically, making the sorting process less time-consuming. Companies like HERA have already adopted AI-based waste sorting to identify materials for reuse and recovery [20].

Mobile applications also play a vital role. Apps like RecycleNation and iRecycle act as digital assistants, helping users locate recycling centers and identify recyclable materials. Educational games available on platforms like the Google Play Store further enhance recycling practices by providing an interactive way for users to ascertain what can be recycled.

Smart waste bins are a prime example of IoT integration. These bins employ sensors to detect trash levels and notify users via mobile devices when they are full [21]. This technology modernizes waste collection and optimizes disposal schedules.

To bridge technology and education, the development of an Augmented Reality (AR) Game offers a distinctive platform for student engagement. AR games incorporate play and exploration into instructional material, which can significantly improve learning outcomes regarding 5Rs concepts [22].

2.4. Educational Game Using Augmented Reality Technology

Developing educational games using Augmented Reality (AR) technology is an effective way to make learning more dynamic. By fusing digital and physical elements, AR allows students to engage deeply with instructional content, utilizing their natural enthusiasm for technology for educational purposes [23] [24].

The development process begins by defining learning objectives and identifying the target audience. Choosing the right AR platform, such as ARKit, ARCore, or Unity with Vuforia—is essential for creating a stable user experience. The game mechanics must align with educational goals, using puzzles or interactive 3D models to make the subject matter accessible [25].

Planning content is critical to maintaining player interest. By using 3D animations and audio, developers can create an immersive environment where students actively interact with the real-world surroundings. Iterative testing is necessary to ensure the AR functions correctly and remains accessible to a wide range of users.

A successful educational AR game must balance fun with informative material. Once thoroughly tested, these games can be launched on app stores and promoted through educational communities to reach a broader audience.

2.5. Augmented Reality Game Techniques

Various AR implementation methods are available to suit different application complexity levels. These techniques ensure that virtual information is displayed with high-quality and accurate graphics.

1. Marker-based AR
   This method uses specific physical symbols or images to trigger 3D animations. The system calculates the orientation of the markers to effectively place digital content [26].
2. Superimposition-based AR
   This technique replaces or augments the appearance of an object by recognizing its spatial elements, such as surfaces or landmarks, without the need for physical markers [27].
3. Markerless AR
   This is a recent development that uses location-based data. The system utilizes GPS, compass, and accelerometer to determine what digital content the user is viewing at a specific location.
   - Each virtual element in a markerless system is assigned specific coordinates.
   - When a mobile device matches these coordinates, the camera displays the virtual product over the real environment.
   - This enables a natural world perception, where computer vision accurately places virtual objects, creating an engaging interactive experience.

2.6. Augmented Reality in Moral Education

AR has the potential to contribute significantly to moral education by providing immersive experiences that foster ethical reasoning and empathy. Through ethical dilemma simulations, students can be presented with moral quandaries in realistic settings. This allows them to make decisions and observe the consequences of their actions in a controlled, virtual environment [28].

Interactive presentations can also convey moral concepts through virtual characters or avatars. These digital guides offer narratives and activities that instruct students on virtues and ethical conduct, leading to higher engagement and better retention of moral lessons.

Furthermore, AR tools allow for self-assessment in character development. Students can reflect on their choices in various scenarios, encouraging self-awareness and the growth of moral values. This interactive approach is also effective in religious education, such as enhancing the understanding of prayer practices [29].

By providing experiential learning opportunities, AR improves upon conventional teaching strategies. It involves students emotionally and intellectually, enabling them to make informed decisions in real-world circumstances.

2.7. Analysis of Existing Systems

Augmented Reality (AR) mobile applications leverage smartphone or tablet capabilities to enhance the physical environment with virtual content [30]. Several existing applications relate to waste management and recycling, each offering unique features:

1. Recycling Assistant

A utility-based app utilizing an AI model for object detection to assist users in identifying recyclable materials.

2. Garbage Gobblers
   An arcade-style mobile game designed to entertain and educate children through interactive sorting tasks.
3. Recycle Game
   A level-based educational game that focuses on waste management challenges using playful graphics.

Despite their advantages, a gap remains for a new AR-driven application that provides an immersive experience specifically tailored for students, linking educational content with interactive real-world events.

1) Comparison of Existing Systems

The following Table 1, it compares the features of existing systems 5Rs-AG: AR Technology Educational Game.

Table 1. Product Comparison Matrix

Criteria \ Name of Product	Recycling Assistant	Garbage Gobblers	Recycle Game
Platform	Mobile App	Mobile App	Mobile App
Have a Scanner at Board-Game	No	No	No
Target user	All ages	For kids	For kids
Provide different challenges	No	Yes	Yes
Provide game tutorial	No	No	No
Provide hint game	No	Yes	No
Provide information in detail about recycling / waste management	Yes	No	No
Educational Game	No	Yes	Yes

2) Limitations of Existing Products

Looking at Recycling Assistant, the app's usefulness is immediately cut short by its geographic restrictions, as it only works in a handful of European countries. The design feels a bit clunky, and the language used is far too complex to keep younger users engaged. Even its core feature, the AI waste scanner can be quite inconsistent and frequently misidentifies what kind of trash you're holding.

As for Garbage Gobblers, it might look fun for little kids, but it seriously lacks educational depth. It completely skips over explaining the actual 5R concepts. Instead, players get stuck in a repetitive loop of just feeding trash to a monster, walking away without learning any real environmental lessons.

Lastly, Recycle Game struggles heavily with basic user experience. The interface design is surprisingly frustrating because it actually lacks obvious navigation options, like a standard home or exit button. With zero tutorials or instructions provided, anyone using it basically has to rely on blind trial and error just to figure out how the game even works.

3) Research Implications and Improvements

Based on the analysis above, the 5Rs-AG application will implement the following improvements to ensure a superior user experience and educational impact:

1. Marker-Based AR Integration
   Utilizing a physical board game as a trigger for AR content to increase student engagement.
2. Enhanced UI/UX
   Developing a user-friendly interface with clear navigation and video tutorials to guide users through the game mechanics.
3. Detailed Educational Content
   Integrating comprehensive information regarding the 5Rs of Zero Waste Management (Refuse, Reduce, Reuse, Recycle, Repair) to ensure users gain theoretical knowledge alongside practical gameplay.

4. Scaffolding Tools
   Including hints and progressive challenges to assist players in achieving higher scores while maintaining motivation.

3. Methodology

To guide the development of the 5Rs-AG: AR Technology Educational Game application, the research adopted the System Development Life Cycle (SDLC) as the most suitable methodology. The following summarizes the approach in a structured way to form the methodology chapter:

1) Research Design and Conceptual Framework

This study follows a structured systems development approach to ensure that the 5Rs-AG application effectively supports its learning objectives. The design integrates Augmented Reality (AR) technology with interactive game elements, targeting students aged 13–15 years to create an engaging educational experience.

2) System Development Life Cycle Phases

The development process is divided into key phases to ensure smooth progress and functional output:

- Analysis Phase:
  User requirements were collected by examining the limitations of existing educational applications. This phase focused on identifying essential components for teaching the 5R waste management concept and evaluating the suitability of marker-based AR as a teaching tool.
- Design Phase:
  In this phase, the application's structure and interface were planned, including UI design, game storyboards, and the creation of 3D assets. The design also considered the placement of AR markers on the physical game board to enhance interaction between the virtual and real worlds.
- Development Phase:
  The actual development was carried out using Unity combined with the Vuforia SDK. Programming the game logic, integrating 3D models, and ensuring proper marker detection according to the planned coordinates were completed during this phase.
- Testing Phase:
  The application underwent rigorous testing to detect bugs and verify smooth interaction between users and AR content. This included checking video tutorials, in-game instructions (hints), and detailed explanations of the 5Rs, ensuring they function without technical interruptions.

3) Hardware and Software Requirements

The following minimum specifications were required to support the development and implementation:

- Software: Unity (Game Engine), Vuforia (AR Engine), and 3D modeling tools.
- Hardware: A smartphone or tablet (Android/iOS) equipped with a camera and gyroscope to enable AR functionality.

4) Evaluation and Usability Testing

The final stage involves assessing usability and learning outcomes. Researchers measured how effectively the application helps students understand the 5R concept and evaluated whether the game elements increased learning motivation and engagement.

4. Findings and Discussion

4.1. Boardgame

Conventional board games often hit the wall of physical immersion. This is where augmented reality (AR) comes in; this technology breaks down those boundaries by offering a completely new dimension of spatial interactivity. In the 5Rs-AG prototype, real and digital space no longer operate separately. They merge. Through the mediation of a smartphone lens, a computing system reads markers on a physical instrument (Figure 1). Five 3D entities are precisely researched onto those real-world coordinates. The result is a compelling visual hybrid.

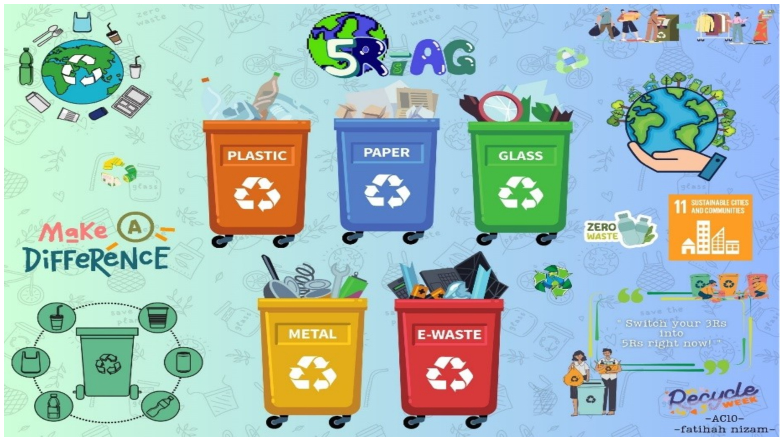

Figure 1. Boardgame for 5Rs-AG App

4.2. Home Page

The homepage bears the crucial burden of being the first point of interaction. If this interface is too noisy, the user's cognitive load will skyrocket. Aware of this fatal risk, the 5Rs-AG visual architecture is built on the principle of reduction, the system displays only what is absolutely essential. Figure 2 demonstrates the simplicity of this design. Three absolute navigation nodes dominantly divide the screen space: "PLAY," "GUIDE," and "EXIT." Very minimalist. Secondary utility elements, such as audio customization and the app's visual identity, are deliberately pushed to the periphery to avoid distractions from the user's sharp focus and ergonomic maneuvers.

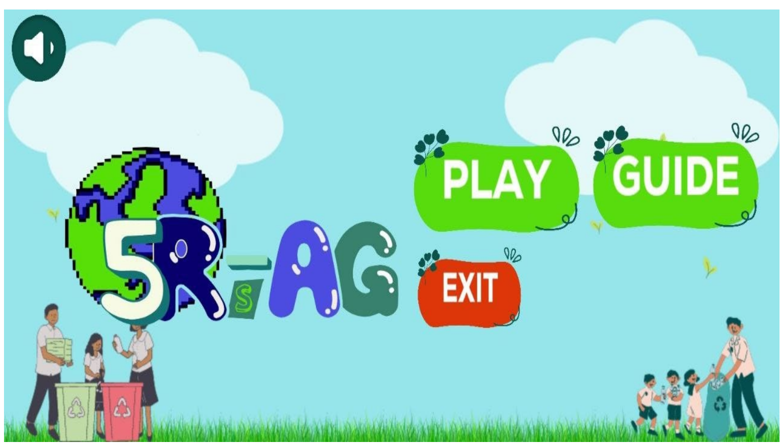

Figure 2. Home Page interface 5Rs-AG App

4.3. Play Game Scene

The essence of 5Rs-AG boils down to one main module: a gamification-based waste sorting simulation. In the bottom right quadrant of the screen, the user controls a trigger actuator. With a single touch, a 3D representation of a specific waste class is instantly instantiated into the game arena. This AR environment (Figure 3) is certainly not left static. Once the marker calibration is complete, a countdown timer automatically pursues the player. Cognitive tension builds. To mitigate the element of blind surprise, the system offers queue visibility in the upper left corner, giving the user little room to formulate microstrategies regarding the probability of the next item. The rules for accumulating points are also very rigid. The algorithm only awards points when the waste researchile lands in a

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valid recycling compartment. Interestingly, to prevent metric manipulation through sporadic interactions (button mashing), the trigger ratio is locked at an absolute one-to-one scale.

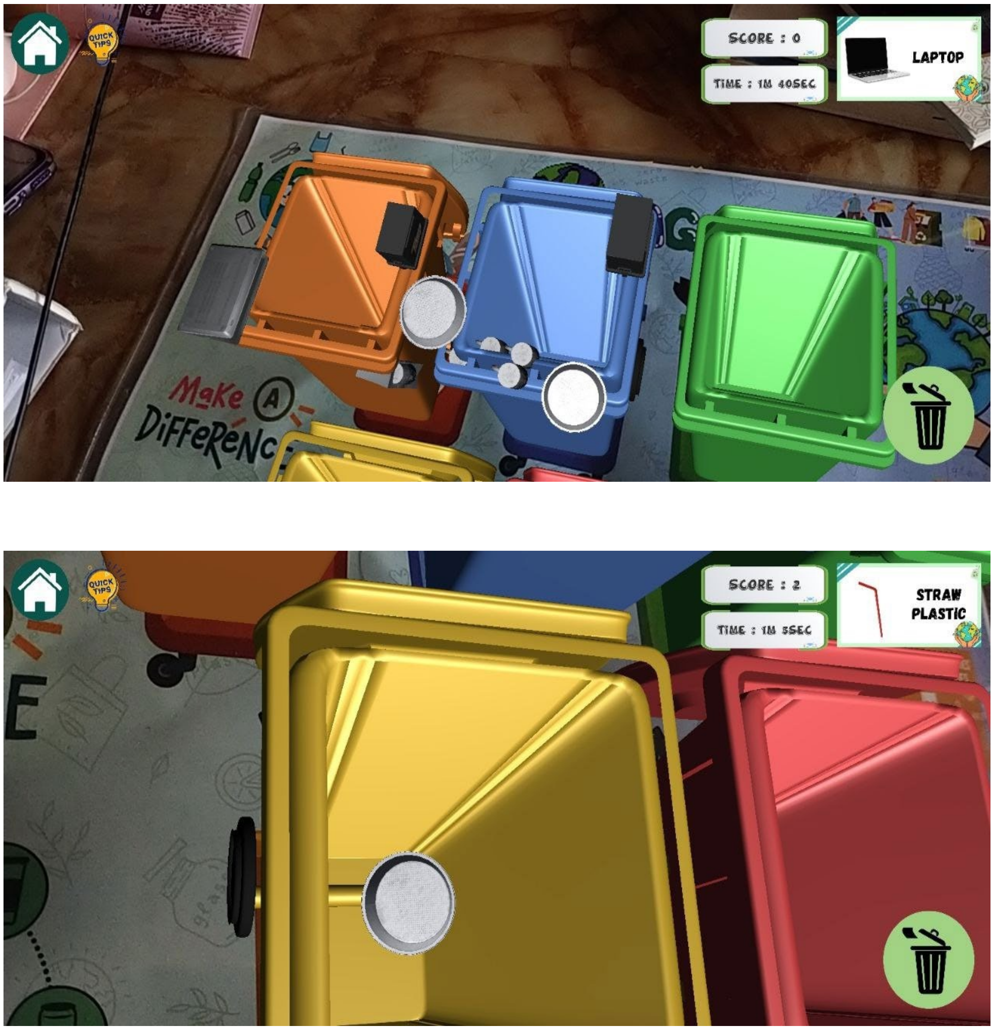

Figure 3. Play Game Scenes Interfaces of the 5Rs-AG App

4.4. Discussion

Table 2 presents the results of the average (mean) score for each statement item in the System Usability Scale (SUS) questionnaire. Table 2 reveals this through the extraction of empirical metrics from the System Usability Scale (SUS) is a psychometric instrument with undeniable reliability in the HCI (Human-Computer Interaction) literature.

The validated figures are very promising. The target audience appears to have adopted this application with almost no operational resistance, particularly regarding its appeal and the steepness of the learning curve. Just look at the spike in metrics for Statement 7 (4.87) and Statement 3 (4.73). These scores provide strong empirical justification that the 5Rs-AG is not intimidating to novice users. Its internal functionalities also interlock elegantly. The consistent consensus scores on Statement 1 (4.67), Statement 5 (4.60), and Statement 9 (4.60) demonstrate strong systemic cohesion. Ultimately, this technical synergy successfully instilled confidence in test subjects, eroding their hesitation when maneuvering within the AR navigation ecosystem.

Table 2. Mean Scores of the System Usability Scale (SUS) Questionnaire

No.	SUS Statement	Mean
Statement 1	I think that I would like to use this AR games application frequently.	4.67
Statement 2	I found the AR games application unnecessarily complex.	4.4
Statement 3	I thought the AR games application was easy to use.	4.73
Statement 4	I think that I do not need the support of a technical person to be able to use this AR games application.	2
Statement 5	I found the various functions in this AR games application were well integrated.	4.6
Statement 6	I think there are not much of irregularities in the AR games application.	3
Statement 7	I would imagine that most people would learn to use this AR games application very quickly.	4.87
Statement 8	I found the AR games application not much cumbersome to use.	3.73
Statement 9	I felt very confident using the AR games application.	4.6
Statement 10	I do not need to learn a lot of things before I could get going with this AR games application.	1.8
	Average Mean	**3.84**

While the usability data shows encouraging numbers, this evaluation reveals the reality of friction that always looms over the adoption of immersive technology. Just look at the plummeting scores for Statement 4 (2.00) and Statement 10 (1.80). Respondents frankly admitted they were confused in the first few minutes of operation; they needed "handholding" or technical guidance before they could start independently. This uncertainty directly correlated with the high complexity metric score for Statement 2 (4.40). Interestingly, this frustration wasn't rooted in poor interface design; it was simply the inherent nature of AR technology itself. Forcing human cognition to simultaneously blend physical reality with digital entities clearly requires a significant leap in adaptation.

On the other hand, respondents' silence on Statement 6 (3.00) and lukewarm scores on Statement 8 (3.73) signal that the system isn't entirely immune to technical glitches. The camera sensor occasionally loses its tracking anchor. Not to mention the soreness in the arm from having to constantly lift the device. The reality of these ten metrics leads to one undeniable conclusion: while 5Rs-AG successfully presents an interactive educational landscape, imposing this technology on novice users without an empathetic onboarding phase and robust system stabilization will only lead to cognitive fatigue.

1) Decoding the Meaning of the SUS Score

Quantitatively, 5Rs-AG successfully secured a final SUS score of 71.35. In industry-standard literature, reaching just 68 is enough to move a system into the "Above Average" or "Good" quadrant.

This means the prototype has already reached the threshold of public acceptance. However, these numbers feel very sterile without being compared to the reality on the ground. The real validation comes from the participants' candid comments. Hearing them label the system as "ideal" or "very engaging" proves that this AR intervention is slowly beginning to shift the outdated paradigm of zero-waste education. Achieving this psychological equilibrium with an early prototype is no small feat, especially considering the painstaking process of stitching a digital interface onto a physical sheet of cardboard.

2) The Reality Behind the Scenes

Bringing this conceptual framework from theory to reality was far from smooth sailing. The execution process was fraught, forcing us to make numerous compromises throughout the implementation phase. The biggest obstacle? The towering learning curve. Dissecting the functional anatomy of Unity and Vuforia from scratch, especially under the looming threat of academic deadlines, was unimaginable cognitive torture. The research team was forced to split. We were programmers, 3D designers, and instructional designers all at once; a multitasking challenge that drastically drained our mental capacity.

As if that weren't dizzying enough, a series of hardware and software anomalies disrupted the work rhythm. In the midst of a crucial development phase, our primary workstation suffered a catastrophic failure. Momentum was instantly shattered. What should have been productive research time evaporated. We were forced to shift our focus to untangling Vuforia's licensing bureaucracy and finding a solution to a highly cryptic APK compilation error. The consequences were palpable: we had to be realistic and sacrifice visual aesthetics for the sake of the system's functional feasibility.

Then there's the classic problem of any academic research: the tyranny of time. The ever-ticking hourglass forced us to be as pragmatic as possible. We cut back on tertiary features. Advanced gamification elements, initially touted as key selling points, such as competitive leaderboards, were ultimately removed from the blueprint. This wasn't an easy decision, but it was the only way to ensure the core functionality modules could operate consistently without the risk of fatal crashes.

3) Future Roadmap

To avoid becoming a mere showcase of academic track records, the application's architecture required massive scale-up.

1) Narrative Transcendence
   The application must move beyond being a mere assignment-dispensing machine. Injecting branching narratives where students' virtual decisions have direct ecological consequences within the game, would spark a much deeper emotional connection.
2) Persistent Tracking System
   Login infrastructure is no longer a luxury, but an absolute necessity. This functionality would transform the application into a legitimate diagnostic tool for teachers to monitor the progress of each individual in the classroom.
3) Physical Material Integrity
   If this research is about environmental sustainability, then the medium must also adhere to that philosophy. Producing a game board entirely from recycled waste will ensure this research truly practices what it preaches. Unifying cryptographic QR codes could also be a neat solution for future commercial distribution licensing.
4) Breaking geographic boundaries
   The ecological crisis doesn't respect national borders. Building tactical alliances with environmental ministries or international NGOs will be a crucial catalyst for localizing the language and spreading the 5Rs-AG ecosystem globally.

5. Conclusion

The 5Rs-AG development experiment ultimately culminated in undeniable empirical evidence. Integrating Augmented Reality (AR) technology into a conventional medium like a board game has proven to be able to breathe new life into the zero-waste education ecosystem. This prototype refuses to be merely a showcase for digital technology. Far from it. It acts as an interactive bridge, successfully translating the rigid abstractions of the Grade 3 Moral Education syllabus into a vibrant and tangible 3D entity. Its primary objective has been fully achieved. We can see evidence of this in the intuitive homepage architecture, through to the dynamic game modes equipped with trash-throwing mechanics and real-time scoring. Of course, this technical precision didn't fall from the sky. The adoption of the Evolutionary Prototyping model throughout the iteration timeline served as a lifeline, ensuring that every graphical curve and line of code never deviated from what the end user truly desired.

What about functional validation? The numbers speak for themselves. Through dissection using the System Usability Scale (SUS) instrument, this prototype successfully achieved a final score of 71.81. A convincing margin. This metric automatically secured 5Rs-AG in the "Good" quadrant, breaking the industry average and demonstrating the high level of respondent acceptance. However, the best validation is rarely purely numerical. This quantitative data takes on a "life" when paired with qualitative responses in the field. Test subjects openly labeled this AR approach as an "ideal" and "very engaging" method for digesting the burden of learning material.

Stopping at this point and being satisfied is clearly not a rational option. This research automatically opens the floodgates for a series of further, far more aggressive explorations to double its impact on the global stage. The most pressing recommendation is the injection of a more vibrant narrative. Embedding storytelling elements into the anatomy of each level will forge a much more personal emotional bond between students and the real-world ecological crisis. Diagnostic

infrastructure can also no longer be ignored. A persistent login system is essential for teachers to maintain full control and track each student's cognitive development directly from the classroom.
For future research, why not align the physical with the philosophy? Printing the game board using real recycled materials is a brilliant move worth exploring. Building strategic alliances with various environmental NGOs will also be crucial for smoothing the application's transition to commercialization. Ultimately, by injecting additional retention features such as competitive leaderboards and a multilingual architecture, 5Rs-AG has the potential to transcend from a local research research to a truly global catalyst for zero-waste awareness campaigns.

Author's Declaration

The authors hereby declare significant contributions to the research process, manuscript preparation, and publication stages.

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