LAUTECH Journal of Engineering and Technology 20 (1) 2026: 175-180

10.36108/laujet/6202.02.0151

Evaluating the Impact of Virtual Reality (VR) Technology in Enhancing Waste Sorting Skills

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Article Info

Article history:

Received: Dec 28, 2025
Revised: Jan 24, 2026
Accepted: Mar 29, 2026

Keywords:

Solid waste,
Sorting, Sustainable,
Virtual reality,
Waste management

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ABSTRACT

The inefficiency of solid waste management in rapidly urbanizing regions such as Lagos, Nigeria, presents a persistent environmental challenge largely driven by inadequate waste sorting at the source. Conventional educational interventions often fail to translate theoretical knowledge into effective waste sorting skills. This study explores the potential of virtual reality (VR) as a tool to improve waste-sorting performance among university students through an interactive, gamified learning experience. A total of 274 participants were exposed to a custom-designed VR module featuring a tutorial, a timed sorting simulation, and a visual feedback system. A baseline assessment of waste management knowledge and technology acceptance was also investigated. This study reported an increase in waste-sorting accuracy (84.5%) with the use of the VR system. The use of visuals to represent different waste categories and the negative impacts of improper waste sorting also increased their knowledge and attitudes towards waste management after exposure to the VR learning environment. This research highlights the potential of VR technology as a viable and impactful tool for bridging the knowledge-skill gap in environmental education and sustainable waste management.

INTRODUCTION

The generation rate of municipal solid waste has increased globally due to rapidly growing populations, economic growth, and affluence (Seshie *et al*., 2020). Waste generation has been projected to reach 2.59 billion tons by the end of 2030. The management of solid waste is becoming more complex due to technological advancements and the widespread use of packaging materials (Assar *et al*., 2025). Environmental challenges such as land and water pollution, greenhouse gas emissions, and the depletion of finite natural resources have been identified with increasing waste generation (Saqalaksari *et al*., 2023). In Nigeria, particularly in Lagos State, waste management challenges are even more pronounced. Rapid urbanisation and population growth have led to increased waste generation, which overwhelms the existing waste management infrastructure. Lagos produces between 13,000 and 15,000 tonnes of waste per day (Akindele, 2022).

Educating the public and creating awareness about the adverse effects of improper waste sorting have proven effective in reducing the burden of waste management. This is supported by the findings of Devi *et al*. (2024). Traditional methods of teaching waste sorting, such as lectures and printed materials, are becoming insufficient to achieve long-lasting change and improve waste-sorting accuracy. These techniques don't effectively engage students, resulting in low awareness and improper sorting and disposal procedures.

Virtual Reality (VR) presents a viable substitute to traditional training and education on waste management. It is a computer-generated immersive experience of simulated reality that frequently includes auditory, visual, and haptic components. VR systems rely on hardware (such as VR headsets) or combinations of devices to accurately detect the position and orientation of the head and other body parts and to send corresponding graphical, acoustic, and haptic data to the user. Immersion, or the feeling of being physically present in a non-physical environment, is the most distinctive feature of virtual reality (Liu *et al*., 2025). This technology can enhance the learning experience, making complex concepts easier to understand. For instance, Vola *et al* (2025) deployed the VR technology in teaching an introductory biology lab course in an American University. They observed increased performance during the students' assessment.VR can also simulate real-life scenarios, allowing students to practice and develop proper waste-disposal habits in a controlled environment. This technology has the potential to improve understanding and retention of waste management practices (Wu *et al.*, 2020; Stenbergt and Makransky, 2023; Chen *et al*., 2023). Although VR technology is now used in some universities in developed countries (Vola *et al.,* 2025), it remains a new learning strategy, especially in developing countries. This research, therefore, aims to develop and evaluate the effectiveness of a custom-designed VR simulation as a tool for enhancing waste sorting skills.

MATERIALS AND METHODS

Study Area and Participants

This research was carried out at the University of Lagos, Nigeria, a public higher education institution in Nigeria. 274 undergraduate students from the faculty of engineering participated in the study. There were 207 males and 67 females, aged 16 to 25 years.

VR-based Equipment Design

Unity Engine as adopted by Saqalaksari *et al*., 2023) was used to create the simulation. It is recognised as a versatile framework for creating interactive 3D experiences with realistic visual outputs. This guarantees its compatibility with VR headsets and streamlines the development process.

The development of the VR simulation focused on two primary areas of 3D asset creation: the simulated environment and the waste materials. The environment was conceptualized to reflect a realistic and familiar setting for the target audience, thereby enhancing immersion. Both visual and auditory aids were incorporated to further enrich the user experience. For asset creation, a combination of custom and external resources was employed. Several 3D models were developed using Blender, a professional open-source 3D creation tool, while additional freely available 3D models were adapted to represent various waste materials. Particular attention was given to ensure that the waste materials accurately reflected their real-world volume, texture, and appearance, thereby promoting authenticity and user engagement (Plate 1). The waste bins were also colour-coded to distinguish between them during sorting (Plate 2).

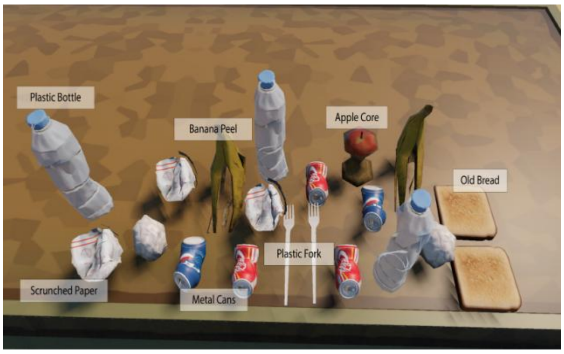

Plate 1: Waste materials used in the simulation

Plate 2: Colour-coded waste bins

Simulation

The choice of simulation was based on previous studies by (Coban *et al*., 2024; Saqalaksari *et al*., 2023). The simulation was designed using Unity Engine 6 and the C# programming language. The virtual reality headsets Meta Quest 3 and Meta Quest 2 were used for testing. The simulation experience consisted of three main parts: a short tutorial, a sorting simulation and feedback.

The participants began the experience with a short tutorial designed to familiarize them with the controls and basic interaction mechanics of the virtual environment. The Tutorial section is a vital introductory component, especially for users who are unfamiliar with VR technology. It helps them feel more comfortable and confident in the environment. This is confirmed by Saqalaksari *et al* (2023). In the tutorial section, a single waste bin and two waste categories were provided. An audio guide instructed the students step by step on how to pick up and drop the waste into the bin. This section takes about one minute to complete, depending on the participants' familiarity with the system and how quickly they adapt to the environment.

In the waste-sorting environment, 20 waste categories were presented alongside 4 waste bins, each representing a different category. The students were instructed to sort each waste item into the appropriate bin. When an item was placed correctly, a "tick" interaction was triggered to provide immediate feedback and reinforce the correct action. The total number of correctly sorted items determined the participant's score.

After completion, the participants were transported to a feedback scene designed to visually represent the outcome of their sorting performance. If all waste items were correctly sorted, a clean and green environment with healthy trees was displayed, symbolizing the positive impact of effective waste segregation (Figure 3a). For scores between 10 and 19, the environment with piles of waste was displayed, reflecting partial effectiveness (Plate 3b), while for scores below 10, a dumpsite featuring waste piles and buzzing of flies was displayed, emphasising the negative consequences of improper waste sorting and disposal (Plate 3c).

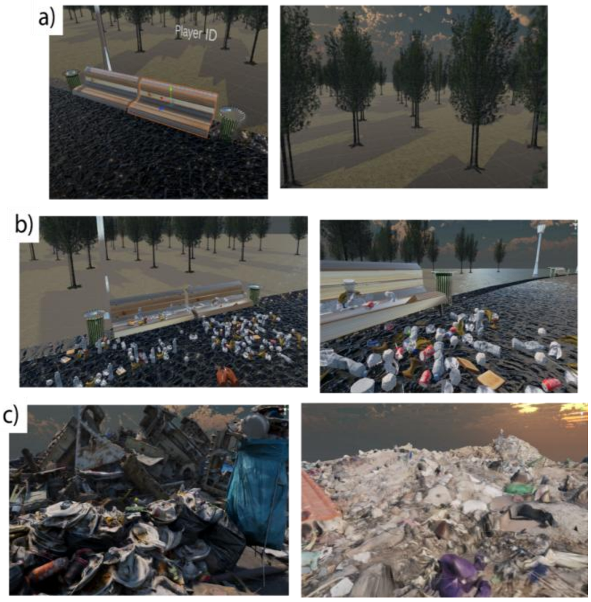

Plate 3(a-c)**:** Feedback scene

Data Collection and Analysis

Data were collected directly from the VR simulation and automatically uploaded to Google Sheets, from which they were later extracted for analysis. Three key performance measures were recorded:

i. Sorting Accuracy (%): This evaluates how students classified waste and sorted items correctly into the appropriate bin.
ii. Sorting Speed (secs): This records the time taken by each student to complete the waste sorting task in the VR simulation.
iii. Raw Sorting Score: This records the number of correctly sorted waste

Administration of Questionnaire

Two sets of questionnaires were developed to evaluate students' understanding of waste management practices and waste sorting, as well as their satisfaction with the VR setting. The first questionnaire was administered before the students accessed the learning simulation, and the second after the training.

RESULTS AND DISCUSSION

The results revealed high performance among participants in the VR environment, demonstrating a strong ability to apply their knowledge in a practical context. The average sorting score was 16.19, which corresponds to a mean accuracy of 80.94%. The majority (95%) of the participants were able to categorise the waste items during the simulation. Regarding efficiency, the VR environment also enhanced the students' efficiency and speed in completing the waste sorting task. The time taken by the participants to complete the simulation varied from 62.77 seconds to 410.63 seconds. The average time to complete the simulation was 146.54 seconds.

Knowledge and Attitude of Participants on Waste Segregation

The results presented in Table 1 showed a significant difference in the pre-test and post-test results after exposure to the VR simulation session. Participants' understanding of waste management and recycling (self-efficacy) increased from 4.56 to 4.74. Similarly, understanding of the environmental effects of improper waste sorting increased from 4.60 to 4.77.

The students were more confident and willing to practice what they had learned through the VR technology, with a commitment to change their attitude towards waste sorting. This is consistent with the study conducted by Rananda Saputra *et al.* (2025), in which participants, through the VR experience, showed improved understanding of hazardous waste management, handling, and packaging procedures. They also found the VR technology helpful and deserving of further usage in waste management education.

Table 1: Pre and Post- Test Scores on Waste Segregation

Measure	Before		After	
	Mean	S.D	Mean	S.D
Self Efficacy	4.56	0.42	4.74	0.36
Knowledge of effects of improper sorting on environment	4.60	0.38	4.77	0.33
Intention to sort waste	4.18	0.42	4.87	0.30

Regarding user experience, participants reported high levels of enjoyment (M = 4.97, SD = 0.28) and substantial interest in the learning content (M = 4.38, SD = 0.59), both measured on five-point Likert scales. Similar results were reported by Weerasinghe (2022) with participants in VR technology reporting high concentration and reduced distractions due to the immersive learning style presented by VR which makes learning fun. In a study conducted in Columbia by Pérez *et al.* (2025), the researchers established increased engagement and less distraction by the students which is similar to this study.

Table 2: Overview of results for user experience

	Mean	S.D
Enjoyment	4.97	0.28
Interest	4.38	0.59
Motion Sickness	1.27	0.53

The students reported minimal motion sickness (M = 1.27, SD = 0.53) while using the VR headset (Table 2). Although earlier research reported potential motion sickness with VR technology (Weerasinghe, 2022; Vola et al., 2025), this study found that the VR environment was generally well tolerated.

CONCLUSION

This study demonstrated the effectiveness of the VR technology in stimulating real-world environments and providing a better learning environment for students. The VR learning experience strengthened students' intentions to sort waste, thereby promoting behavioural change towards waste sorting. The students were more confident and enjoyed the VR learning environment. Our findings indicate the need to incorporate new technological tools, especially VR, to complement conventional instructional tools in waste management. It is recommended that future research focus on comparing conventional learning tools for waste sorting with the VR learning platform in a larger test group across other non-science disciplines within the university environment.

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