Research

Uncovering the drivers of intent to use the metaverse: diverse experiences in sustainability education

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Abstract
This study investigates how technological and pedagogical factors influence students' intention to engage with virtual worlds on educational metaverse platforms and examines the resulting learning outcomes in sustainability education. Traditional sustainability education often fails to effectively engage students with real-world challenges. Metaverse platforms provide immersive, interactive environments that bridge theoretical knowledge with practical application but face usability, complexity, and user comfort issues that can hinder engagement and learning. Using a mixed-methods approach, 54 undergraduate students from Hong Kong and the Philippines participated in sustainability modules via the Classlet metaverse platform. Regression analysis revealed that Ease of Use, Enjoyment, Perceived Performance, and Immersion accounted for 77.1% of the variance in intent to engage. Ease of Use and Enjoyment were the strongest positive predictors, while higher Immersion negatively impacted VR users, indicating that excessive complexity reduces usability. Additionally, gaming experience influenced enjoyment, with weekly gamers reporting higher engagement. Desktop users showed the highest intent to use the platform, whereas VR users experienced greater immersion but also more discomfort. Qualitative feedback highlighted the platform's engaging and innovative features alongside technical and navigational challenges affecting learning outcomes. These findings highlight the need to balance interactivity, usability, and adaptability in educational technologies. Recommendations include implementing adaptive learning pathways, enhancing onboarding processes, and offering customizable interaction levels to accommodate diverse learner needs. Refining immersive learning approaches can better connect theoretical concepts with real-world sustainability applications, fostering increased student engagement and improved learning outcomes.

Keywords Metaverse-based education · Education for sustainability · Immersive learning

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1 Introduction

Immersive learning technologies have transformed education, creating new possibilities for knowledge acquisition and comprehension. In sustainability education, where complex, interdisciplinary challenges require innovative teaching approaches, traditional methods often fall short. This research explores how metaverse-based learning can bridge this gap, fostering deeper student engagement through immersive and interactive experiences.

1.1 Revisiting the educational model

Sustainability education entails tackling complex, interdisciplinary problems demanding innovative solutions [22]. Conventional methods often lack the hands-on learning needed for deep problem-solving. To address this, we employ metaverse technology to create realistic simulations that enhance student interactions in virtual reality (VR) [12]. Such simulations place students in real-world scenarios, encouraging deeper thinking and practical problem-solving–especially important for fields like sustainability and entrepreneurship [13]. Realistic, varied, and interactive settings encourage authentic environments that mirrors real-world complexities.

Some examples of engaging methods in sustainability education are highlighted by Wong and Wong [35] and Markowitz, Laha, Perone, Pea, and Bailenson [24]. Wong and Wong [35] enhanced sustainability education using a private social media platform where students documented daily waste habits, then reviewed peers' content for more purposeful learning. Markowitz et al. [24] showed that VR field trips deepen cognitive associations with scientific topics–helping students learn, recall, and retain complex concepts like ocean acidification.

While VR can uses simulations and 3D environments to create engaging experiences, metaverse platforms provide persistent, interconnected virtual spaces for interaction, exploration, and content customization. Combining virtual and augmented reality with user-generated content and social interactions, the metaverse offers a more expansive and dynamic environment than standalone virtual reality (VR) [11]. The platform' built-in tools let administrators quickly build and customize content, reducing setup time [36].

1.2 The metaverse as a transformative educational platform

Dwivedi et al. [11] delve deeper into the potential of the metaverse as an educational tool. They focus on four distinct interrelated dimensions: an environment that can showcase both realistic and unrealistic realms, interfaces ranging from simple 3D to immersive VR, complex interactions that go beyond mere conversation, and social activities that encourage peer-to-peer engagement. The metaverse also converges virtual and augmented realities, offering multisensory experiences and user-generated content. In this context, 'presence' refers to the physical feeling of being in a virtual space [8]. 'Reflection' involves connecting virtual experiences with real-world contexts, helping students make meaningful connections between what they encounter in virtual environments and their daily lives [16].

Furthermore, Kye, Han, Kim, Park, and Jo [19] explore the possibilities of the metaverse in education, emphasizing its capacity to create and augment virtual environments. Learners can participate in a mix of real-world and virtual experiences, offering a unique educational approach that mirrors, extends, and even transcends real-life scenarios. Kye et al. [19] also discusses how virtual reality simulations leverage visuals connected to real-world objects, effectively bridging the gap between the virtual and physical realms. They note that the metaverse can replicate real-life environments and create entirely new virtual worlds, providing diverse immersive experiences. Additionally, the metaverse enables the logging and tracking of user experiences, which can help analyze and enhance learning outcomes within these virtual spaces. Studies, such as Yang, Ren, and Gu [37], demonstrate the use of the metaverse in sports education, particularly in teaching basketball skills and rules. Sun et al. [32] shows its application in digital medicine, where complex medical information and collaborative experiments can be facilitated.

1.3 Integrating narrative and experiential learning for enhanced engagement

Narrative transportation transforms learners from passive observers to active participants through storytelling [33]. In VR, these narratives unfold in interactive, 3D environments that heighten emotional engagement [15]. As a result, learning becomes more realistic and engaging. Liu [20] found that when narrative transportation is based on real-world environmental perspectives, it can motivate students' intentions. This occurs due to the promotion of emotional connections with nature and the strengthening of positive attitudes. Omori, Shigemoto, and Kitagawa [26] further illustrates the use of VR in medical education. It helped students practice essential infection control procedures, such as hand hygiene and wearing personal protective equipment.

Santilli, Ceccacci, Mengoni, and Giaconi [27] conducted a systematic review comparing the effectiveness of VR with traditional methods in higher education. Their findings suggest that VR enhances student engagement, interactivity, and learning outcomes, particularly in STEM disciplines. However, challenges remain in fully integrating VR into education. They note that VR research has been disproportionately focused on STEM fields, particularly Health Sciences, with limited exploration in Humanities and Social Sciences. This is particularly relevant for subjects like sustainability.

Aksel Stenberdt and Makransky [1] found that VR significantly improved waste sorting knowledge and self-confidence. However, instructional strategies like problem-solving challenges and exaggerated feedback require further examination to understand their full impact. They suggest that future designs should place students directly in affected environments to enhance engagement and provide more immediate, impactful feedback for behavior change.

Kleinlogel, Schmid Mast, Renier, Bachmann, and Brosch [17] examined VR' use in promoting energy-saving behaviors, finding it more effective than traditional methods like print or video. They suggest that future interventions could incorporate multi-user experiences in virtual communities practicing sustainability. Social reinforcement mechanisms–such as leaderboards, shared goals, or collective rewards–could enhance norm activation. Additionally, simulating the real-time environmental consequences of one' actions could increase emotional investment and drive behavior change.

1.4 Addressing educational challenges through pedagogical innovation

Although VR tools are widely accessible, traditional pedagogy can still limit critical thinking and problem-solving, which VR might help to overcome. Luna-Nemecio et al. [22] advocate for learning approaches in sustainable development that involve multiple stakeholders and perspectives. VR environments, where avatars represent varied roles, can integrate these viewpoints into a cohesive, experiential format–particularly useful for tackling real-world challenges like climate change.

However, Checa and Bustillo [4] highlight a limitation: many VR serious games are isolated experiences and lack integration into broader learning methodologies. Their study found that only 30% of the studies demonstrated that VR games improved learning outcomes, while 10% showed no clear advantage over conventional methods. This gap shows VR tools must integrate with broader pedagogical strategies to improve cohesiveness and impact. Additionally, Saritaş and Topraklíkoğlu [28] observed that many educational applications in the metaverse fail to engage students in meaningful interactions. They suggested creating active learning environments based on experiential learning and gamification, with an emphasis on real-life scenarios and appropriate pedagogical integration to enhance learning.

Researchers like Doerner and Horst [9] and Araiza-Alba, Keane, Chen, and Kaufman [2] have explored practical approaches to active VR learning. Doerner and Horst describe the "circuit parcours technique," where students rotate through a series of VR stations, each focusing on a different task or concept, similar to stations in circuit training exercises. This technique aims to promote active participation by immersing students in diverse VR scenarios. Similarly, Araiza-Alba et al. demonstrate the potential of VR in teaching problem-solving skills through engaging tasks, such as the river crossing game, which enhances participation and interest. This approach is aligned with Kolb' experiential learning theory, which describes learning as a cycle that includes direct experience, reflective observation, conceptual understanding, and active experimentation [18].

While these methods illustrate the benefits of active learning in VR, it remains unclear how "active" the learning must be to optimize interactions with content and gain knowledge outcomes. The degree to which active participation influences learning effectiveness is not yet fully understood. Addressing complex topics such as sustainability, which involve multiple stakeholders and intricate real-world issues, may require more advanced VR environments to truly enhance the ability of learners to appreciate different point of views and dilemmas.

1.4.1 Exploring the efficacy and acceptance of metaverse-based educational tools

A key challenge in metaverse or VR platforms is sustaining attention beyond the first 15 min [3]. Immersive experiences rely heavily on user preferences, which underscores the need for intuitive interfaces [30]. However, Maddox and Fitzpatrick [23] notes the complexity of the issue. These environments activate experiential, cognitive, behavioral, and emotional components of the brain. If not carefully managed, this involvement can overwhelm learners, leading to a lack of understanding of the content. For instance, Chen, Wang, and Wang [5] highlights how the absence of authentic linguistic and cultural contexts in some VR scenarios, such as in language learning, can hinder learners' ability to connect meaningfully with the material.

Integrating these insights, we explored the relationship between technological and pedagogical factors in the metaverse. Fussell and Truong [14] identifies key factors such as perceived enjoyment and ease of use, which are crucial for shaping the user experience and willingness to engage with metaverse platforms. Fussell used an extended Technology Acceptance Model (TAM) to study how aviation students perceive VR for flight training, focusing on ease of use, usefulness, and enjoyment. The research showed that VR can enhance skill development and participation, making it a valuable training tool. Building on this framework, Lopez-Ozieblo, Wong, Shen, and Daniel [21] incorporated motivational, cognitive, and social factors, showing their impact on learning outcomes in VR classrooms. Similarly, Mengoni, Hwang, Shen, and Li [25] explored interactive content in metaverse learning, finding that user engagement and perceived performance are critical predictors of technology acceptance.

High-immersion VR, which uses head-mounted displays and motion tracking, provides greater sensory realism and interactivity. In contrast, low-immersion VR, typically screen-based, offers simpler navigation and lower cognitive demands. Chen et al. [5] found that high-immersion VR enhances cognitive, behavioral, and social engagement more than low-immersion VR. However, its impact depends on the learner's characteristics and the task type. Similarly, Yudintseva [38] noted that while high-immersion VR fosters authenticity and engagement, it can also increase cognitive load and motion sickness. For some users, low-immersion VR is preferable. Our analysis suggest that the benefits of immersion depend on context, including users' VR experience, spatial ability, and cognitive effort.

Our investigation aims to examine how user-related technological factors and instructional approaches affect students' willingness to engage with educational metaverse platforms and the resulting impact on their learning outcomes. This is crucial, as previous studies, such as Donnermann et al. [10], highlight how the combined use of social robots and gamification can overwhelm learners with excessive interactions and stimuli, potentially affecting their focus and hindering effective knowledge acquisition.

Therefore, we propose the following research questions.

- Research Question 1 (RQ1): How do technological and pedagogical factors influence students' intention to engage with virtual worlds on educational metaverse platforms?
- Research Question 2 (RQ2): What are the consequences of their learning outcomes?

2 Method

We adopt a mixed methods research design to holistically examine the impact of metaverse-based tools on students' engagement and learning outcomes. Our approach incorporates both quantitative and qualitative data collection and analysis methods, based on the VR adapted technology adoption framework proposed by ussell and Truong [14].

2.1 Participants

The study involved three modules on environmental science and sustainability: two based in Hong Kong and one in the Philippines. All students enrolled in these respective course modules were invited to join the educational activity. However, participation in the research was voluntary. At the end of the activity, the students were invited to complete a self-reported survey, which included a section to indicate their consent to participate in the study. By entering their names in the online form within the survey, the students provided their informed consent for their data to be included in the research. Students were also given the option of opting out of completing the survey without repercussions. Details of the survey are provided in Section 2.4.

In total, 54 students agreed to participate by completing the survey, with detailed demographic data from the participants and distributions of the groups provided in Table 1.

Participants who did not choose to complete the tasks or survey were excluded. There were no additional exclusion criteria based on demographics or data quality. Outliers were not removed, as the data reflected subjective self-reports and responses were deemed critical to understanding participant experiences.

Given the trade-offs between high and low immersion VR [5, 38], we prioritized ecological validity to create an environment that reflects real world conditions and accommodates diverse users. High-immersion VR can enhance engagement,

Table 1 Study participants across three groups

Category	Group 1	Group 2	Group 3
Participants	17	15	22
Topic	Waste Management (science)	Transitional Environments (design)	Waste management (science)
Age	17-19 undergraduate	17-19 undergraduate	17-19 undergraduate
Gender	15 Female, 1 Male, 1 Prefer not to say	18 Female, 3 Male, 1 Prefer not to say	14 Female, 1 Male
Gaming Frequency	53% non weekly, 47% weekly	27% non weekly, 73% weekly	53% non weekly, 47% weekly
Device	47% mobile, 18% desktop, 35% VR headset	45% desktop, 55% mobile	13% desktop, 87% mobile
Location	Hong Kong	Hong Kong	Philippines

but can also introduce cognitive strain and accessibility barriers, while low-immersion VR offers greater ease of use and broader applicability. To maintain flexibility, participants were allowed to use their personal devices, such as a mobile or desktop, and could opt for virtual reality when available in the class.

2.2 Platform

To create the learning simulations, we utilized the Classlet metaverse platform. The platform supports the construction of interactive virtual worlds by educators and students through custom mapping of content to avatars in 3D scenes. Classlet also includes data analytics, which we used to gather detailed information about user interactions within these environments, including student actions, interactions, and responses to the scenarios.

Three key features of Classlet include:

- Template-Based Content Creation: The platform simplifies the process of creating educational content using templates and spreadsheets. This allows educators to efficiently organize instructional materials, such as descriptions, questions, and activities.
- Web Dashboard for Analytics: The platform provides a web dashboard where educators can upload, monitor, and analyze data about student interactions within virtual environments. The real-time editing feature of the dashboard offers the necessary flexibility for dynamic course management.
- Auto-Mapping from Content to Scene: This feature automatically translates educational content into virtual scenes, reducing the manual effort typically required and improving the efficiency of content deployment.

In the non-headset version (mobile/desktop), students tapped on stars with their mouse or fingers to initiate tasks and used the UI to make selections. They tracked their progress through an on-screen quest progress log. Dialogues appeared on-screen, and multiple-choice questions provided immediate feedback. For complex tasks, such as manipulating 3D objects, students could tap directly on objects or grab and drop them into designated panels. Participants could also adjust the camera view by dragging the screen (mobile) or using the mouse (desktop) to rotate and zoom. In the headset version (Meta Quest 3), the UI was integrated into 3D space, and participants interacted by selecting, grabbing, and placing objects using hand tracking and controllers, while head movement naturally controlled the camera for an immersive experience.

The base scenes and models are custom-created to maintain relevance and quality for the learning objectives.

2.3 Activities

The activities were designed to facilitate an interactive and exploratory learning environment, allowing the student groups to immerse themselves in specific topics of environmental sustainability.

Group 1: Waste to Biogas and Methane Pollution: The students engaged in activities such as sorting compostable and non-compostable items to gain foundational principles of waste segregation, while designing a sustainable menu helps to minimize food waste. Interactions: Participants interacted with expert avatars through dialogues, voice interactions, and AI-driven responses. They answered multiple choice questions on sustainability topics, completed object placement tasks, and solved scenario-based challenges. Activities included optimizing carbon sequestration, managing pest control, and selecting eco-friendly solutions, building their awareness of sustainability concepts in the metaverse.

Group 2: Hydrosolar Plant - Solar Panel Recycling and Chemical Pollution: This topic introduced students to the life cycle of solar panels and understanding chemical pollution to gain insights on renewable energy systems and responsible recycling practices. Interactions: Participants interacted with avatars to investigate renewable energy, the circular economy, and environmental issues. They answered multiple choice questions, identified malfunctioning systems, assessed reports, and sorted materials. Scenario-based tasks involved chemical spill investigations and improvements in energy efficiency. Image and PDF analysis provided deeper insight into floating solar systems and hybrid renewable energy solutions.

Group 3: Mango Farm - This topic introduces students to sustainable practices in mango orchard management and integrating renewable energy to reduce landfill dependency and adopting circular economy principles in agriculture. Interactions: Participants interacted with avatars through dialogues, answered multiple choice questions, and completed object placement tasks related to sustainable agriculture. They received AI-driven feedback, engaged in voice interactions, and solved challenges such as optimizing farm resources, selecting eco-friendly practices, and managing waste. These tasks required students to make decisions, plan strategies, and apply sustainability solutions relevant to real-world mango orchard management.

In each thematic group, students were assigned to complete a series of at least 15 activities in the metaverse, designed to be completed in approximately 60 min. These activities were accessible on desktop, mobile, or tablet devices. At the beginning of the session, each participant was briefed on the study objectives and the mechanics of using the Classlet platform. A two-minute introductory video was provided explaining the objectives, platform navigation, tasks, and download instructions. The participants were then given one hour to complete the tasks, where the learning flow is shown on Fig. 1. Students provided post-activity feedback through a Likert scale survey.

Figure 2 shows screenshots of these Classlet activities in action. Classlet allows educators to upload and manage content in the metaverse, simplifying the scene creation process. The platform enables the selection of interaction types and the integration of visual elements, such as images and instructional content, to directly integrate learning objectives, creating personalized learning experiences aligned with educational goals, as shown in Fig. 3.

2.4 Data analysis and collection

Data analysis for this study consisted of both quantitative and qualitative components, collected through a self-reported survey that combined Likert scale items, multiple choice questions, and open-ended questions to capture student engagement and learning outcomes. We examine how technological and pedagogical factors shape students' intention to engage with the metaverse platform.

2.4.1 Quantitative analysis and methodology

Quantitative data were gathered from Likert scale and multiple-choice items based on the framework proposed by Fussell and Truong [14], with survey questions described in Table 2. Descriptive statistics were calculated for each construct

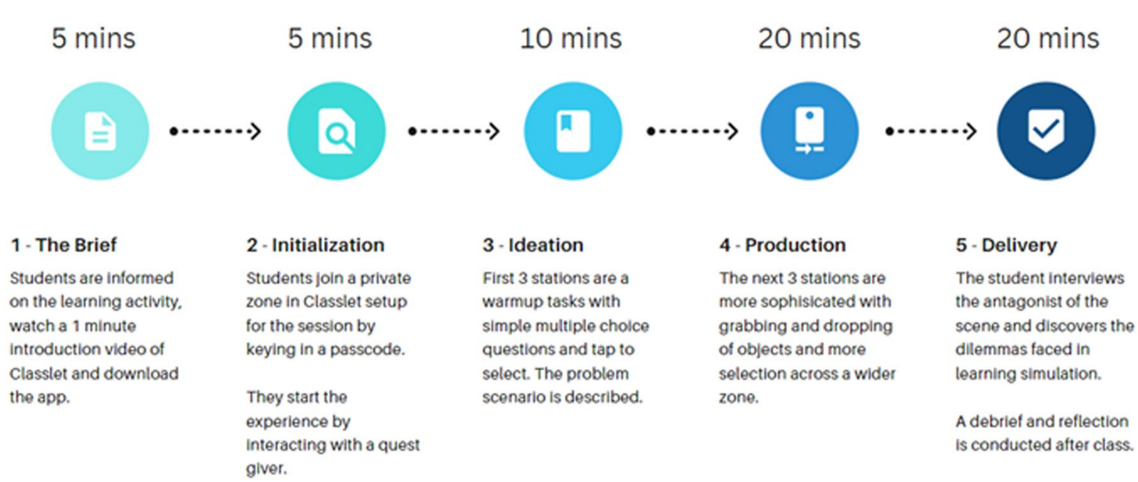
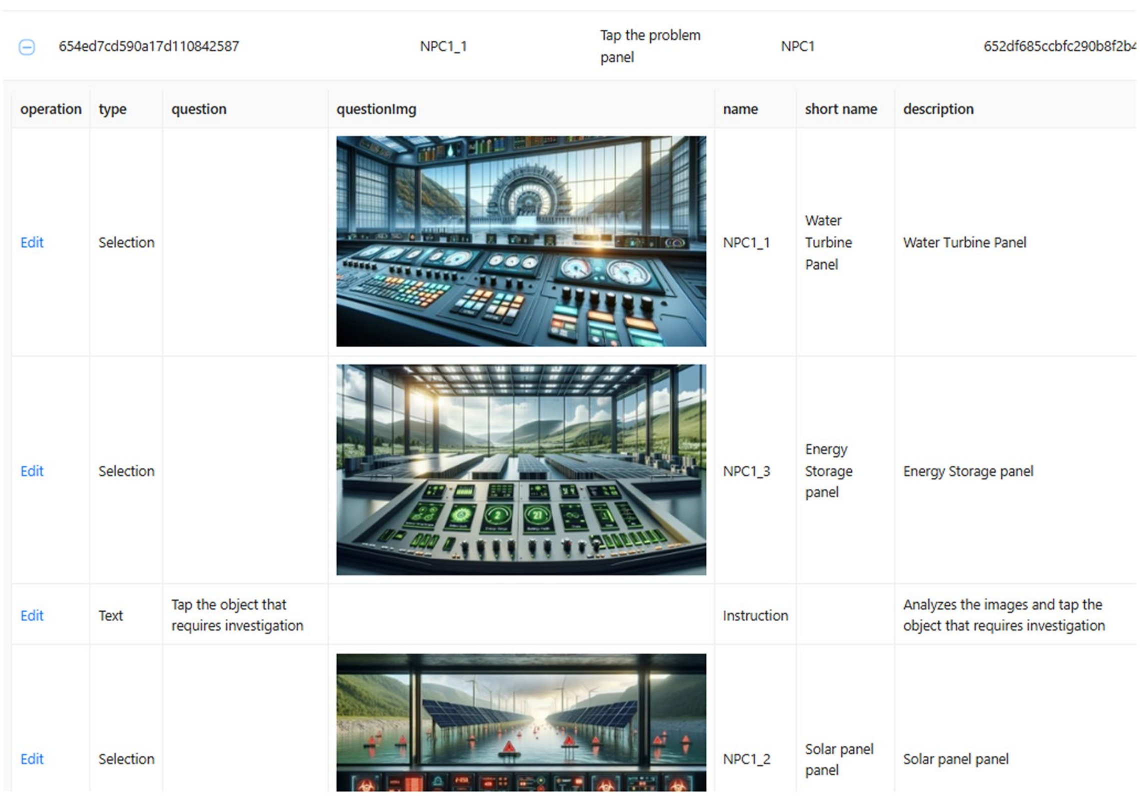


Fig. 1 Learning flow for the activity, illustrating the step-by-step progression for learning on the metaverse platform

Fig. 2 Screenshots from the VR environment showcasing key activities and interactions the features on the metaverse platform



⊖ 654ed7cd590a17d110842587			NPC1_1	Tap the problem panel	NPC1	652df685ccbfc290b8f2b4
operation	type	question	questionImg	name	short name	description
Edit	Selection			NPC1_1	Water Turbine Panel	Water Turbine Panel
Edit	Selection			NPC1_3	Energy Storage panel	Energy Storage panel
Edit	Text	Tap the object that requires investigation		Instruction		Analyzes the images and tap the object that requires investigation
Edit	Selection			NPC1_2	Solar panel panel	Solar panel panel

Fig. 3 Images uploaded by the educator for the selection task on the metaverse platform to support learning objectives

(e.g., attitude, enjoyment, ease of use, intention to use, perceived health impact), including mean scores, standard deviations, and ranges.

As the data deviated significantly from normality ($p < 0.001$), non-parametric methods were applied. Specifically, Mann-Whitney U tests were used to compare engagement levels between participants who participated weekly versus

Table 2 Survey Constructs and Corresponding Questions

Construct (Code)	Questions
TECH1 (Technology)	The resource provides a highly immersive virtual experience.
TECH2 (Technology)	The user interface of the resource is intuitive and easy to navigate.
TECH3 (Technology)	Interactive elements within the resource function smoothly and as intended with no significant issues.
AT1 (Attitude)	Using metaverse for learning is a good idea.
AT2 (Attitude)	I feel positively toward using metaverse for learning.
EASE1 (Ease of use)	Learning to use metaverse for learning will be easy for me.
EASE2 (Ease of use)	It will be easy to gain skills for my subjects using metaverse.
ENJ1 (Enjoyment)	Using metaverse for learning would be enjoyable.
ENJ2 (Enjoyment)	I enjoy using immersive simulation technology such as metaverse.
PERF1 (Perceived Performance)	Using metaverse for learning is more productive than other e-learning methods like videos or slides.
PERF2 (Perceived Performance)	Using metaverse for learning will improve my knowledge or skills more efficiently than traditional methods like videos or slides.
USE (Usefulness)	Learning using metaverse will be useful for gaining knowledge in the real world.
INTENT1 (Intent to use)	If made available, I am willing to use metaverse for learning.
INTENT2 (Intent to use)	If made available, I intend to use metaverse for learning.
BEH1 (Behavioral Control)	I could use metaverse for learning if no one was around to tell me what to do.
BEH2 (Behavioral Control)	I could use metaverse for learning if I had only a virtual instructor guiding me.
HEALTH (Health impact)	Using metaverse may negatively affect my physical health.

nonweekly and between different device groups (desktop, mobile, and VR). Additionally, correlation analysis was used to assess the relationships between constructs such as attitude, enjoyment, and intention to use. Spearman's rank correlation was employed due to the non-normal distribution of the data. Finally, a regression analysis was performed to identify predictive relationships between constructs. Multiple regression analysis was used to explore how variables such as ease of use, enjoyment, and attitude could predict intent to use and learning outcomes.

To account for variability in factors like device type, and gaming frequency, bootstrap estimates with 5000 replicates were applied within the regression analysis. This method provided more reliable coefficient estimates and ensured the stability of findings across different data subsets.

We conducted subgroup analyses for the variables identified as covariates in the overall regression analysis, particularly on gaming frequency, across the Desktop, IOS, and VR groups. These analyses used ANOVA to examine the significance of these covariates. We found that only VR showed significant results for TECH, whereas low-immersion groups had strong enjoyment effects via ENJ1.

The data for task completion times, was extracted from Classlet to derived the recorded start and end times of each task for every participant. These timestamps were used to calculate the total duration for each participant, and then the average time per task was computed by dividing the total duration by the number of tasks completed within each group. The data were segregated by group (Group 1, Group 2, and Group 3), and the average task completion times were then plotted, with the total duration on the y-axis and the number of tasks completed on the x-axis. This allowed for a visual comparison of the time efficiency and task completion rates, showing that the experience across groups was relatively similar in terms of task completion speed and overall efficiency.

2.4.2 Qualitative data analysis and insights

The qualitative component was captured through two open-ended survey questions, allowing students to provide detailed feedback on their experience with the metaverse platform. This feedback provided valuable insights into how students interacted with the tool and their perceptions of its performance. The responses were then analyzed using thematic analysis, a process that involved identifying and categorizing recurring themes across the data.

To ensure the robustness and reliability of the analysis, the two raters jointly reviewed the first 20 responses to determine the key categories. This initial collaboration allowed them to refine the coding framework, which was subsequently applied independently by the raters. Each rater was tasked with independently coding the responses to identify key themes, including engagement, interaction with avatars, usability, and perceived real-world applicability. After the initial stage, the remaining responses were independently coded, and the identified themes were compared and refined as needed.

To assess the level of agreement between the two raters and ensure consistency in the coding process, Cohen's Kappa was used. This statistical measure provided an indication of inter-rater reliability, ensuring the accuracy and consistency of the thematic categories identified.

2.4.3 Study validity, reliability, and generalizability

As the data collected were self-reported, no pre-processing steps were required. No adjustments were necessary for multiple comparisons, as only a single regression model was tested. Outliers were not excluded as the data represented subjective experiences and the elimination of responses could affect the interpretation of general trends.

A priori power analysis was performed using G * Power, aiming for a power of 0.9 and an effect size of 0.35. A sample of 53 was required to detect significant effects with four predictors. This effect size was chosen based on the VR adapted Acceptance Model (TAM) [14] which describes relationships between ease of use, enjoyment, and performance expectancy. Furthermore, the application of TAM is supported by the analysis of metaverse affordances as described by Shin [31]. Shin emphasizes that immersion and engagement in augmented reality are influenced not only by technological factors but also by user preferences, social interactions, and embodied cognition. This aligns with the focus of TAM on ease of use and enjoyment as critical components of user acceptance in technological environments. The ability to create empathy and foster social interactions, with avatars, through immersive experiences highlights how TAM can be adapted for pedagogical purposes within the metaverse.

This study includes participants from two countries to examine the generalizability of VR adoption in various educational settings. Prior research has demonstrated the effectiveness of virtual reality using the same platform and instrument applied [21, 25]. We extend this work by exploring VR' role in sustainability education and assessing its impact in different cultural and contexts. Although the results were not analyzed separately by country, this approach provides broader insights into VR adoption and establishes a foundation for future cross-cultural research.

In our study, the gender distribution was highly imbalanced, with 47 female and only 5 male participants. As such, we did not perform analysis based on gender, as the imbalance would undermine the reliability and validity of such comparisons. On the other hand, this gender imbalance could be seen as an opportunity to further explore insights into female participants' engagement and learning outcomes in virtual environments.

3 Results

3.1 System results

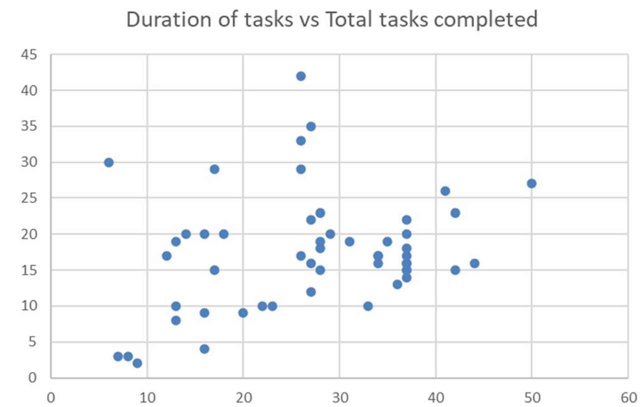
- Group 1: Out of 17 participants, a total of 276 tasks were completed, averaging 16 tasks per participant. The group took 280 min to complete all tasks, resulting in an average task completion time of 1.00 min per task.
- Group 2: Out of 15 participants, a total of 451 tasks were completed, averaging 30 tasks per participant. The group completed all tasks in 263 min, with an average task completion time of 1.71 min per task.
- Group 3: Out of 22 participants, a total of 691 tasks were completed, averaging 31 tasks per participant. The group took 367 min to complete all tasks, with an average task completion time of 1.88 min per task.

In plotting the overall time versus task completion, we obtained the graph shown in Fig. 4, which illustrates the distribution of task completion times against the number of tasks completed across participants. This graph reveals a largely normalized completion rate, indicating that the task completion time was relatively consistent between participants, with no significant outliers or skewed data points. The even distribution of task completion times suggests that the different groups worked at comparable paces, strengthening the consistency of the process and the reliability of the metaverse platform for task-based education.

3.2 Quantitative results

For the descriptive statistics of our study, we analyzed data from 54 valid responses. The mean scores ranged from 2.796 to 4.204. The average score for INTENT (computed from INTENT1 and INTENT2) was 3.806, reflecting moderate intent to

Fig. 4 Duration of task completion versus total tasks completed



continue using the method. The standard deviations indicated moderate variability, ranging from 0.810 to 1.323. The top 3 highest mean scores were: AT1: 4.204 ENJ1: 4.056, ENJ2: 4.056. These high mean scores suggest that the participants rated their attitude and enjoyment highly. In particular, the results of the Shapiro-Wilk test were significant ($p < .001$) for all variables, indicating deviations from the normal distribution; therefore, the following statistical analysis was performed using nonparametric versions since the data was not normalized.

Device subgroup descriptives:

- Desktop users (15) had the highest intention to use (4.47), usefulness (4.33), and satisfaction (4.53), suggesting a stronger willingness to adopt and a consistently enjoyable experience. They also reported the highest behavioral intention (4.13) and lower Health Perception concerns (2.93), indicating better perceived control and comfort.
- iOS users (32) had moderate scores on all metrics, with Attitude (3.28), Ease of Use (3.28), and Intent to Use (3.88) falling between Desktop and VR. They also had the lowest Health Perception concerns (2.63), indicating fewer discomfort issues, though their Enjoyment (4.00) was slightly lower than Desktop and VR.
- VR headset users (6) had the highest Attitude (4.33) and Ease of Use (4.00), showing strong engagement but also the highest Health Perception score (3.67), indicating greater discomfort concerns. Their Intent to Use (3.33) and Behavioral Intent (3.67) were the lowest, suggesting that while VR was seen as effective, concerns about usability and comfort may have influenced adoption.

In terms of reliability, the reliability of the frequentist scale (Cronbach's α) for the overall scale was high at 0.904. However, HEALTH negatively correlated with the scale, which was expected since it was formulated in the inverse direction (5 for more impact while 1 for less).

A Mann–Whitney U test (the nonparametric version of the independent t-test) comparing participants who participate weekly versus nonweekly revealed a significant difference for ENJ1 ($W = 262.500$, $p = 0.041$, rank-biserial correlation $= -0.264$), indicating that weekly users reported significantly higher enjoyment compared to nonweekly users, with a small effect size.

The intradimension correlations (Spearman's rho, the nonparametric version of Pearson's correlation) showed significant consistency within each construct, with strong relationships such as AT1 and AT2 ($p < .001$) and ENJ1 and ENJ2 ($p < .001$), confirming internal reliability. For the Intent variables, INTENT1 was strongly correlated with AT1 ($p < .001$), EASE1 ($p < .001$), and ENJ1 ($p < .001$), identifying Attitude, Ease of Use, and Enjoyment as top predictors of intention to use the metaverse method. The cross-dimension correlations were also significant, with EASE1 correlated with ENJ1 ($p < .001$) and PERF1 ($p < .001$), indicating that ease of use improves both enjoyment and performance perceptions.

In our regression analysis, a "Residuals vs. Predicted" plot did not show a discernible pattern, supporting the assumption of linearity. The residuals exhibited constant variance, confirming homoscedasticity, and a Q-Q plot indicated that residuals were approximately normally distributed with minor deviations at the tails. Multicollinearity was not an issue, as all predictors had values of the variance inflation factor (VIF) well below 10. The Durbin-Watson statistic was 1.821, indicating residual independence and no significant autocorrelation.

The model explained 77.1% of the variance in average intent ($R^2 = 0.771$), demonstrating a strong predictive relationship. This model was statistically significant, $F(6, 47) = 26.396$, $p < .001$, indicating that the combined predictors were effective in predicting students' intent to use the metaverse.

The individual predictors in the regression model were:

- Tech: B = −0.258, p = 0.004 (negative effect). Higher perceptions of the platform's technological immersion were associated with lower intention to use it. This suggests that increased immersion might detract from user intent, potentially due to overwhelming complexity or reduced usability.
- EASE1 (Ease of Use):B = 0.398, p <.001 (positive effect). Participants who found the platform easier to use were more likely to report a higher intent to use the platform, reinforcing the importance of user-friendly design in engagement.
- ENJ1 (Enjoyment): B = 0.463, p <.001 (positive effect). Enjoyment was the strongest predictor of intent, showing that participants who enjoyed their experience in the metaverse were more likely to continue using it.
- PERF2 (Perceived Performance): B = 0.226, p = 0.022 (positive effect). Participants who believed the metaverse improved their learning performance were more likely to report higher intent, highlighting the role of perceived benefits.
- USE1 (Usefulness): B = 0.205, p = 0.051 (borderline significance). Perceived usefulness positively influenced engagement intent, although this effect weakened when gaming frequency was included in the model.

Based on the predictors TECH, EASE1, ENJ1, PERF2, and USE1 in our regression covariates, we conducted a series of subgroup tests, including ANOVA and Kruskal-Wallis tests, to assess their significance. Comparisons by gaming experience did not yield significant results. For the course topics, only the Desktop group showed significance in the ANOVA, while Kruskal-Wallis did not reveal any significance. The results show the following:

- For the Desktop group, EASE1 (F(3, 11) = 1.250, p = 0.339) and TECH (F(2, 10) = 1.246, p = 0.329) were not statistically significant. All other predictors were significant.
- For the IOS group, TECH (F(3, 28) = 2.371, p = 0.092) was not significant. All other predictors were significant.
- For the VR group, TECH (F(1, 4) = 21.778, p = 0.010) was significant. However, USE1 (F(1, 3) = 15.000, p = 0.030) was significant in ANOVA, but Kruskal-Wallis (3.333, p = 0.068) was not significant, indicating a discrepancy between the tests. Other predictors were not significant.

In addition to the standard regression results, bootstrap estimates were also calculated based on 5000 replicates to provide a more robust evaluation of the model coefficients. The bootstrap coefficients, which are based on the median of the bootstrap distribution, confirm the significance of several predictors, such as Tech (p = 0.002), EASE1 (p < 0.001), and ENJ1 (p = 0.003), while Frequency (Weekly) remained non-significant (p = 0.863). This bootstrap analysis serves as a reliability check on the model's coefficients, accounting for potential variability and providing a more accurate estimate of their confidence intervals.

Although frequency (weekly participation) were not significant predictors of Avg Intent (p = 0.950), their inclusion in the model produced a suppression effect on the USE1 coefficient (from p = 0.047 to p = 0.051).

Regression analysis revealed that device type was not a significant predictor of intent, indicating that variations in hardware–whether mobile, desktop, or VR–did not systematically influence participants' intent to engage with the learning content. Notably, the number of participants using each device type was not evenly distributed, which may have affected the ability to detect potential differences.

A post hoc power analysis was performed in G * Power to assess whether our sample of 54 participants was sufficient to detect the observed effects in the regression model for Average Intent. With an observed R^2 of 0.771, we calculated an effect size f^2 of 3.37. With four predictors and a significance level of 0.05, the power was 1.00, confirming the reliability of our results.

3.3 Qualitative results

Below, we categorize participants' open-ended survey feedback. This analysis was performed using thematic analysis, with two independent raters scoring the responses. Cohen's weighted kappa for interrater agreement was 0.916, indicating a strong level of consistency between Rater 1 and Rater 2 across the evaluated categories. The scores were closely aligned in areas such as "Technical issues" and "Enhanced understanding and retention," with only a one-point difference. Slightly larger discrepancies appeared in categories such as "Usability and Navigation" and "Innovative Use of Technology," where the differences ranged from 3 to 5 points. These minor variations reflect subjective differences yet do not undermine the generally high interrater agreement.

3.3.1 Positive

- *Engagement and Enjoyment* This category captures how enjoyable and engaging the learning experience is. Positive feedback focused on the interactive and fun nature of the method, which made learning feel like a game. Quotes: "It's fun, interactive and feels like a new experience," "Great for visualizing the topic; makes learning a more interactive experience", "Interactive, entertaining, and provides a sense of accomplishment through tasks and questions".
- *Innovative Use of Technology* This category highlights the novelty and creativity of using advanced technology in learning. The users appreciated the creativity of the platform and the immersive potential of using VR. Quotes: "It is very innovative and feels like a practical, game-like experience", "Advanced and innovative; I like how it' a new style of learning".
- *Enhanced Understanding and Retention* This category addresses how well the platform aids in comprehension and memory retention through VR. Users noted the value of visualization and the immersive environment for better memory retention. Quotes: "The immersive experience makes it easier to memorize the knowledge.", "Eye-catching and helps make learning a more visual experience.", "Easy to enjoy the process of gaining knowledge with an immersive experience."

3.3.2 Opportunities

- *Technical Issues*This category addresses functional and operational issues within the platform, affecting its performance and reliability. Commonly mentioned issues include bugs, lag, navigation challenges, and high device requirements. Quotes: "The game had a bug wherein it kept spinning on its own, making me really dizzy.", "Too many bugs that could affect the learning progress, and the way we play is only walking and clicking.", "It requires a device and internet; the graphics are not very smooth."
- *Usability and Navigation*This category covers the intuitiveness of the user interface and the ease with which users can interact with the platform. Participants noted difficulties with navigation, instructions, and layout. Quotes: "A bit hard to navigate, needs internet connection, and the game needs to be learned prior to use," "The text is small, not easy to find the direction, not easy to follow the concept the game wants to deliver,", "Controls are confusing to navigate, and some choices are not fully visible."
- *Learning Effectiveness and Engagement*This category reflects the educational value of the platform and the way in which users engage in learning. Feedback highlighted mixed results in maintaining attention, with some reporting enjoyment and others finding it distracting. Quotes: "I focus more on the movement of the NPC and the game scene, which disturbs my attention on the knowledge and information of the topic.", "Visuals not related to the learning experience may distract learners.", "Time-consuming and may be difficult to facilitate more in-depth exchanges."

4 Discussion

Our study shows how immersive methods such as VR in a metaverse platform, can boost engagement in sustainability education. Five main predictors emerged as significant in explaining students' intent to engage with metaverse-based learning: EASE1 (Ease of Use), ENJ1 (Enjoyment), USE1 (Usefulness), PERF2 (Perceived Performance) and TECH (Immersion).

4.1 Influence of pedagogical factors on students' intention to engage

Three of the five predictors–ENJ1 (Enjoyment), PERF2 (Perceived Performance), and USE1 (Usefulness)–suggest that the learning method promoted active learning.

Enjoyment (ENJ1) scored a mean of 4.056 and strongly predicted intent to use ($B = 0.463$, $p < 0.001$). Comments like "It' fun, interactive and feels like a new experience" highlight the platform' enjoyable features. This aligns with flow theory [6], which emphasizes engagement when challenges match learners' skill levels and feedback is immediate. In our study, participants described tasks as neither too easy nor too difficult, and they received system responses, conditions that fostered a "flow state" and boosted enjoyment.

Perceived performance ($p = 0.022$) helped students feel that the method improved learning outcomes. Participants reported that the immersive experience made it easier to understand and retain concepts, noting it "makes it easier to memorize the knowledge" and "helps make learning a more visual experience."

Our findings align with prior studies showing that VR can encourage engagement through active learning [2, 9]. Although these activities demonstrate success in applying active learning, addressing complex topics such as sustainability requires more nuanced design, particularly with regard to technological factors.

Some participants found the method distracting, despite giving a 73.3% average perceived performance rating. One student mentioned, "I focus more on the movement of the NPC" while another stated, "Visuals not related to the learning experience" To address this, future iterations should refine scene design to help learners focus on core objectives and reduce off-task distractions.

Although attitude (AT1) showed a strong correlation with intent (INTENT1, $p < .001$), it was not a significant predictor in the regression model. This suggests that factors like ease of use and enjoyment have a more direct influence on learning intent. The high correlations between attitude and ease of use (0.700) and enjoyment (0.709 and 0.749) imply that attitude shapes students' perceptions indirectly, but usability and enjoyment ultimately drive intent. While fostering positive attitudes is beneficial, creating an engaging, easy-to-use platform is essential for sustained use. To improve attitude, it is important to clarify the activity's purpose and goals to participants, rather than presenting it as merely a game. To do this, we provided a pre-session video and explainer to help students understand the content.

According to Self-Determination Theory (SDT) [7], fostering autonomy and competence is crucial for sustained motivation. Participants felt more autonomous because navigation and tasks were straightforward. They developed competence by successfully applying new skills in real time. These factors likely explain why ease of use and enjoyment emerged as strong predictors of engagement.

4.2 Influence of technological factors on students' intention to engage

Ease of Use (EASE1) was a significant predictor of intent to use, with a positive effect ($B = 0.398$, $p < 0.001$). However, some participants reported usability issues in the qualitative feedback. Issues such as "a bit hard to navigate" and "controls are confusing to navigate" were common, indicating challenges in the platform's usability. Other feedback mentioned technical issues like "bugs" and "lag," which detracted from the overall learning experience and could have influenced perceptions of Ease of Use negatively.

Despite a positive correlation between Ease of Use and intent, technical issues and usability concerns affected students' interaction with the platform. Finding the right balance between task complexity and ease of use is important. Simplifying some aspects, such as task navigation or overall design, could make the platform more engaging and improve the learning experience.

Our findings on immersion and intent align with Chen et al. [5], which found that lower immersion led to higher learning outcomes while maintaining authenticity. Yudintseva [38] suggests that while high-immersive VR provides more engaging and emotionally rewarding experiences, it also increases cognitive load and discomfort, which may reduce students' willingness to communicate. Low-immersive VR, while less engaging, offered a more manageable experience. This might explain why participants in the low-immersion VR group showed higher intent to use the platform (per the mean scores). To improve this, simplifying tasks, reducing interaction complexity, and enhancing user instructions could make the experience more accessible and boost engagement.

Many studies, such as those by Yudintseva [38] and Chen et al. [5], explore the effectiveness of high vs. low immersion VR modalities, often emphasizing that high-immersion VR tends to produce more interactions. However, our results offer a more nuanced perspective. Our subgroup analysis showed that only the VR group had significant results for TECH ($p = 0.010$), indicating that higher immersion in VR may drive greater intent. In low-immersion environments, ENJ1 was found to be significant, with the Desktop group ($p = 0.005$) and IOS group ($p < .001$) both showing strong effects on enjoyment. Interestingly, the VR group showed no significant result for ENJ1 ($p = 0.219$), suggesting that the use of VR headsets may be more driven by the immersion or embodiment.

Interestingly, participants in Group 1 completed their tasks significantly faster, averaging 1 min per task, compared to 1.88 min (Group 2) and 1.71 min (Group 3). It is unclear why this discrepancy exists. Several possible factors could have contributed, including differences in task complexity, engagement levels, prior familiarity with the content, or variations in device usage. Additionally, Group 1 had a higher percentage of VR users, which may have influenced task execution speed. Another possible explanation is the role of the tutor or facilitator. Different instructors may have employed varying levels of guidance, scaffolding, or instructional styles, which could have impacted how students navigated tasks. A more directive tutor might have led students through activities more quickly, while a more exploratory or discussion-driven approach could have encouraged deeper engagement, affecting time spent on each task.

4.3 Impact of gaming experience on engagement and learning outcomes

The inclusion of weekly gamers as a predictor caused a suppression effect on the USE1 coefficient, reducing its significance from $p = 0.047$ to $p = 0.051$. Further, our U-test results revealed that gaming frequency significantly influenced enjoyment, a key predictor of intent to use the method. This suggests that gaming participation may have a more substantial impact on learning outcomes than initially expected. These findings contrast with Warden, Stanworth, and Chang [34], which suggested that nongamers only experience a slight disadvantage in virtual learning environments. It should also be noted that our results, based on a predominantly female sample, may limit the generalizability of these findings.

Bavelier and Green [3] highlight that action video games, commonly played by gamers, excel in graphics and action elements, making it challenging to create serious games that match this level of engagement. Additionally, Shaker, Togelius, and Nelson [29] discuss the challenges of procedural content generation in metaverse environments, which must balance diverse content with high quality to ensure effective learning experiences. Thus, the challenge is not only incorporating metaverse tools but also meeting gamers' expectations for engagement and content quality.

Experienced gamers may expect clear, actionable outcomes from the metaverse, leading them to critically assess the platform' efficacy. Meeting these expectations requires flexible, dynamic game design with narrative-driven engagement and interactive challenges. Aligning the educational experience with the exploratory gameplay and personalized interactions familiar to gamers, while maintaining educational goals, could better meet these expectations.

A custom onboarding tutorial or pre-session class tutorial can provide more training for participants with less gaming experience. Since class time is limited and the platform alone may not always be sufficient to bridge the gap, instructors may need to take a more active role in addressing differences in user familiarity.

4.4 Implications for designing metaverse platforms

Luna-Nemecio et al. [22] emphasize the importance of fostering complex thinking in sustainability education, aligning well with the problem-solving nature of metaverse platforms. Farrell [13] highlight the need for authentic experiences that replicate real-world challenges. The metaverse, with its ability to simulate environmental issues, encourages deeper engagement with sustainability topics, enabling students to tackle complex systems. Our investigation demonstrates the use of avatars and 3D interaction, enhancing student involvement and understanding of sustainability.

Active learning methods, such as those proposed by Araiza-Alba et al. [2] and Doerner and Horst [9], are crucial for promoting critical thinking and student engagement. Our findings support this, as activities like object manipulation, scenario navigation, and real-time feedback align with these principles. Additionally, our approach aligns with Kolb' experiential learning theory, which emphasizes the importance of active participation in the learning process. Immersing students in a dynamic metaverse environment encourages hands-on problem-solving and real-time reflection.

Effective metaverse platforms should prioritize design considerations that address learner needs and the capabilities of metaverse platforms:

To create an effective and engaging educational metaverse platform, it is essential to prioritize key design considerations that address both learner needs and the unique capabilities of metaverse technology. These include:

- Balancing Immersion and Usability: Ensuring the platform is intuitive and user-friendly is essential to keep learners engaged without overwhelming them. For example, offering adaptive immersion allows users to adjust the level of interactions based on their comfort and experience. A less experienced learner might prefer a less immersive environment with simplified controls, while more experienced learners may benefit from deeper immersion and more complex interactions.
- Adaptive Learning Pathways: Adaptive learning pathways tailor experiences based on users' prior knowledge and familiarity with VR. Implementing personalized onboarding through assessment quizzes can guide users to appropriate learning levels, helping those with less experience navigate simpler tasks while offering advanced options for more experienced learners to explore.
- Gamification and Engagement: Gamified elements like points, leaderboards, and narrative-driven challenges can boost motivation. Personalizing avatars and introducing rewards for task completion will sustain learners' interest, while story arcs related to learning objectives deepen dialogues, making the experience more immersive and memorable for students.

- Interactive Design: Practical interactions in metaverse platforms could include tasks like manipulating 3D objects to simulate environmental changes, decision-making scenarios where students select sustainable practices and observe their impact, and collaborative problem-solving activities like designing eco-friendly systems. Students could participate in role-playing simulations, taking on roles such as policy makers to address sustainability issues.
- Real-World Connections: Create scenarios that mirror real-world challenges, such as sustainability projects, where learners can assume varying avatar roles (e.g., community planner, environmental activist, or local government official). These roles simulate real-life decision making and foster deeper empathy, allowing students to explore different perspectives while solving complex issues.

4.5 Alignment with theoretical models and prior research

The overall predictors in this study highlight that metaverse platforms can foster complex thinking essential to understanding sustainability topics. The metaverse' learning experiences enable first-hand exploration of diverse environments. This finding aligns with Luna-Nemecio et al. [22], who emphasize the need for complex thought in the education of sustainable development. The significance of this can be seen in the predictive variables for perceived usefulness and performance, reflected in a positive mean score (3.898). This is in line with the findings of Wong et al. [36], which reported that pedagogical factors had a greater impact than technical ones.

In comparison, Aksel Stenberdt and Makransky [1] found that virtual reality significantly improved knowledge and self-confidence, suggesting that placing students in affected environments could enhance engagement and provide more immediate feedback for behavior change. Our analysis supports this notion, as metaverse platforms foster interactive learning environments, aligning with their recommendation to directly involve students in context-specific experiences.

Our findings show that both the extended VR technology adoption model [14] and Shin [30], which stress interactive elements for effective learning. Students described the experience as 'interactive' and enjoyed exploring, which aligns with research on narrative-based engagement [20, 33].

Similarly, Kleinlogel et al. [17] found that VR is more effective in promoting behavior change, particularly in sustainability, compared to traditional methods. They highlight the potential of multi-user experiences and social reinforcement mechanisms like leaderboards and shared goals. Emphasizing engagement through the metaverse, aligns with their suggestion that social and collective experiences can motivate students toward sustainable behaviors. Indeed, the use of a quest system, avatars, and missions in our platform fostered a dynamic environment where social and narrative-driven elements helped maintain motivation–further reflecting the autonomy and competence described in SDT.

Variables such as intuitiveness of the interface, functionality, behavioral control, and health, often cited in studies for their impact on user experience, particularly with respect to dizziness and navigation issues, did not emerge as significant predictors of intent. Although several students reported challenges with controls and dizziness, the lack of significance of these variables suggests that they may not be critical to overall experience or that the novelty of the metaverse platform overshadowed these difficulties.

Post hoc power analysis further strengthens these findings, achieving a power of 1.00. The high power based on the observed R^2 of 0.771 confirms that the sample size was adequate to detect significant relationships among key predictors. However, the exceptionally high power and effect size may also suggest potential overfitting, as the model may be overly tailored to the specific dataset.

In sum, the metaverse platform fostered autonomy and competence (key SDT tenets), prompting many students to describe the experience as 'fun' and 'game-like.' These findings are further supported by the Technology Adoption Model' [14] key variables–enjoyment, perceived performance, ease of use, and immersion–which together underpinned students' positive attitudes and sustained the learning experience.

Limitations. The study's limitations stem from the early stage of metaverse platform in education, which may affect the replicability and effectiveness of the findings. Although the study tests the acceptability of metaverse and VR among students, it focuses primarily on engagement without evaluating actual learning outcomes such as knowledge retention or application.

Additionally, the small sample size, drawn from Hong Kong and the Philippines, limits generalizability, and the short duration of exposure to VR can also restrict the applicability of the results. Future studies could involve larger, standardized samples to improve generalizability.

The notably lower task completion rate for Group 1, compared to Groups 2 and 3, requires closer examination. Several factors could have contributed to this discrepancy, including curriculum design, device usage, and participant dynamics:

- *Device Usage* Group 1 had 35% of participants using VR headsets, while Groups 2 and 3 only completed the tasks on non VR headsets. VR headsets, while immersive, can pose usability challenges for first-time users, such as difficulties with navigation and dizziness, potentially slowing task completion. Additionally, the imbalance in the distribution of device types across groups limits direct comparability, as outcomes could be influenced by both the level of immersion and individual comfort with the metaverse platform.
- *Topic Engagement* Group 1's focus on "Waste to Biogas and Methane Pollution" may have been perceived as less engaging compared to the tasks in Group 2 (Solar Panel Recycling) or Group 3 (Mango Farm Sustainability). Tasks involving food (Group 3) or technology (Group 2) may have been more appealing, motivating participants to complete more tasks.
- *Classroom Dynamics* Group 1 had a higher percentage of non-weekly gamers (53%) compared to Group 2 (27%). Non-gamers may have struggled with the interactive elements of the platform, requiring more time to adapt and navigate the tasks. Further, the tutor's facilitation style across groups may have influenced task completion speed and thus the student interactions or behavior. Future studies should standardize tutor involvement.

Cultural differences, such as learning styles and comfort with technology, may shape students' responses to VR. For instance, participants in this study, drawn from Hong Kong and the Philippines, may have differing educational contexts that influenced their engagement. This study also primarily reflects the experiences of female participants due to the gender imbalance. Future research should explore a more balanced sample to assess these differences.

5 Conclusion

This study explores how technological and pedagogical factors in metaverse learning influence student engagement and learning outcomes. Key findings indicate that 'Interesting' delivery methods significantly boost interactions, particularly through immersive experiences that are visually and emotionally resonant, proving especially effective for complex sustainability topics. The study highlights the importance of authentic and narrative assessment to improve learning in the metaverse.

In addition, the research recognizes the metaverse as a potentially transformative educational platform, offering dynamic and interactive environments that effectively blend theoretical and practical learning. However, it also brings to light the emerging challenges and constraints in this field, such as technical requirements, user interface issues, and the early stage of metaverse platform development, particularly in education.

In particular, the analysis focuses primarily on participation rather than on a comprehensive exploration of learning outcomes. Thus, this is a gap in understanding the full educational impact of metaverse tools, which warrants future investigation.

These findings contribute to the ongoing discourse on metaverse education, suggesting that despite current obstacles, the incorporation of innovative, interactive delivery methods holds promise to enhance educational experiences across various disciplines. As further exploration continues, the potential of the metaverse to transform learning is becoming increasingly evident. Future research, particularly in learning outcomes and AI enhancements, will be crucial to unlocking and understanding the full capabilities of this emerging educational frontier.

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Data availability The datasets generated and analyzed during the current study are available in the Figshare repository, https://doi.org/10.6084/m9.figshare.27985523. The data include statistical results, timestamp and duration data, systematic data, and self-assessed survey results.

Declarations

Ethics approval and consent to participate The research was ethically approved by the Sub-Committee on Research Ethics and Safety of the Research Committee at Lingnan University, Hong Kong (Ref. no. EC176-2324). Prior to participation, all students were informed of their rights, the voluntary nature of the study, and their ability to withdraw at any time without consequences. At the end of the activity, students provided explicit consent by entering their names in an online form within the self-reported survey or chose to opt out of the survey entirely. The study was conducted in accordance with the guidelines governing research involving human participants, as outlined by Lingnan University.

Consent for Publication Not applicable

Competing interests Jiandong Daniel Shen owns stock in Classlet. The authors declare that this does not affect the study's objectivity.

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