ENHANCING ENGINEERING EDUCATION ON CIRCULAR ECONOMY IN WATER SYSTEMS LEVERAGING MIXED REALITY

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Yu-Chen Lee, Ph.D (corresponding author)
Maseeh Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin
ORCID: https://orcid.org/0000-0001-7479-9968
yuchenlee@utexas.edu

Fernanda Leite, Ph.D., P.E., F.ASCE, Joe J. King Professor
Maseeh Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin
ORCID: https://orcid.org/0000-0002-7789-4474
fernanda.leite@utexas.edu

SUMMARY: *The traditional linear economy model of water resource management, which follows a take-make-use-dispose pattern, is increasingly inadequate in meeting the rising demand driven by population growth and climate change. In contrast, the circular economy, which emphasizes the repeated use of water, has been proposed and advocated as a promising alternative over the past few decades. Nevertheless, research endeavours have yet to reach the public in an efficient way, resulting in a gap of public engagement in circular economy adoption. With advancements in computing power, this study investigates the potential of mixed reality (MR) technology to enhance learning about circular economy in water systems, focusing on engineering students. The authors compared the MR-based learning approach with conventional learning methods leveraging a proposed quantitative workflow. Fifty engineering students participated in a controlled experiment to assess learning outcomes. The findings significantly highlight the effectiveness of MR with 27.1% improvement of assessment scores, surpassing the 11.5% improvement gain from the traditional learning approaches. This research underscores MR's potential in translating complex ideas into more accessible format. Future research will expand participant diversity and apply MR to other sectors, enhancing public understanding and adoption of circular economy concepts.*

KEYWORDS: *mixed reality, circular economy, Microsoft® HoloLens 2.*

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1. INTRODUCTION

Water is one of the most essential elements for human survival. However, approximately 771 million people around the world lack access to safe drinking water (World Health Organization and United Nations Children's Fund, 2021). Additionally, industrial and agricultural activities, extreme weather events, and population growth have further exacerbated global water crisis (The World Bank, 2021). The World Economic Forum in 2021 identified global water crisis as the fifth most critical risk, given its wide-ranging potential effects on social, economic, and environmental aspects (World Economic Forum, 2021). Thus, it is crucial to tackle the worldwide water challenges for individuals and communities, strengthening the immediate need for collaborative action from public and private sectors, and citizens.

One major cause of the water shortage is the traditional linear economy model, which follows a take-make-use-dispose pattern (The World Bank, 2021). This model consumes vast quantities of fresh water for resource extraction and industrial processing, and often releases polluted wastewater after use, further contaminating available resources. That is, raw materials are extracted for manufacturing products, which are eventually disposed after consuming, generating waste and pollution. This traditional linear approach is environmentally and economically unsustainable, as it depletes extensive natural resources without replenishing them. With a rapidly growing population, the linear economy is increasingly insufficient to meet the demands, as natural resources are limited. In response to this, the concept of circular economy has been proposed in recent years. A circular economy model is promising to mitigate water crises through closing the loop of water resources, thus promoting repeated use of water. This approach can lead to lower water usage and waste by reducing, recovering, restoring, recycling, and reusing water resources (Blomsma and Brennan, 2017; Morseletto, 2020; The World Bank, 2021). Incorporating circular economy concepts in urban water systems is beneficial, as it can create more resilient and inclusive cities, providing equitable services for vulnerable groups, and preparing cities for unexpected shocks (The World Bank, 2021). The benefits of a circular economy extend beyond conserving water and reducing waste, encompassing social, economic, and environmental advantages, thus underscoring the necessity for a transition from a linear to a circular economy model.

While numerous researchers placed emphasis on the implementation of circular economy in water systems (Bouziotas et al., 2019; Eshetu Moges et al., 2018; Gleason Espíndola et al., 2018; Lee et al., 2023a; Makropoulos et al., 2018; Roest et al., 2016; Smol et al., 2020; The World Bank, 2021), an efficient way to reach the general public is still far from being settled. In fact, low public engagement is often identified as one of the major barriers to adopting circular economy concepts (Guerra and Leite, 2021; Lee et al., 2023a).To be more specific, the general public may have difficulty accessing research articles, and publications require professional knowledge to digest thus are challenging for an average citizen to comprehend. To create a bottom-up culture that widely embraces circular economy principles, it is important to enhance public awareness. In this regard, strategic and effective communication methods are necessary to raise public consciousness of the importance of the circular economy and its potential to address global water shortages. This can encourage behavioural changes among individuals and advocate for policy changes among stakeholders, thereby supporting the paradigm shift to a circular economy. Changes in both individual behaviours and policies can pave the way for the broad implementation of circular economy concepts within the water sector, contributing to the development of more resilient, sustainable, and inclusive water systems.

Building upon this understanding, visualization technologies emerge as potential tools to bridge the gap between complex concepts and the public's comprehension. Visualization has been recognized as having increasing impact on environmental planning and policy, given its capacity of simplifying complicated information or knowledge and making it more memorable and accessible (Metze, 2020). Visualization techniques, ranging from infographics to 3D modelling, can effectively translate intricate ideas or data into engaging and understandable formats. Through the use of visualization, the potential advantages and impacts of adopting circular economy concepts can be vividly conveyed, strengthening understanding and appreciation among the general public. As a result, policy makers can establish informed discussions with the public and encourage their support for necessary policy changes, thereby leading to wider adoption of circular economy in the water sector.

Advancements in Extended Reality (XR), including Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR), are rapidly revolutionizing numerous industries, including education. These visualization technologies share the benefit of offering more interactive, immersive, and engaging experiences that enhance the learning process and foster an inclusive environment catering to a variety of needs (Adami et al., 2022; Billinghurst and Duenser, 2012; Cheng et al., 2023, p. 360; Ogunseiju et al., 2023; Quintero et al., 2019; Sakib et al., 2021). Incorporating the strength of AR and VR, MR technology offers a hybrid and seamless experience where users can interact with both digital and physical objects. While VR delivers full immersion, it disconnects users from their surroundings, which may induce discomfort or anxiety (Dodevska et al., 2025; Papaefthymiou et al., 2024) and limits its suitability for topics grounded in real-world contexts. Conversely, AR often lacks the depth of interactivity needed to explore complex, multilayered systems (Negrão and Maciel, 2024; Radu, 2014). MR was therefore selected for this study as it enables interaction with complex 3D data while maintaining awareness of the physical environment (Begout et al., 2022), effectively situating the abstract and often "invisible" urban water system within physical space. The authors explored the use of MR as an efficient teaching method, aimed at effectively communicating circular economy knowledge, starting with engineering students. As future designers, policymakers, and technical experts, their understanding is critical for the implementation of these complex systems. The authors proposed a framework that leverages the Microsoft® HoloLens 2 MR technology to educate users about circular economy principles in urban water systems. Its feasibility was validated through comparative evaluation with traditional teaching methods. This methodology supports the development of MR educational applications to promote the circular economy and can be applied to various urban systems beyond water.

2. BACKGROUND RESEARCH

In recent decades, advancement in digital visualizations has led to a revolution that information is store and communicated in different ways (Cheng et al., 2024; Skaaland and Pitera, 2021). For example, Building Information Modeling (BIM) and Geographic Information Systems (GIS) have been largely used in infrastructure projects, enabling more efficient and seamless flow of data collection and exchange. The use of digital visualization was found to be helpful in improving communication with the public and stakeholders, eliminating barriers associated with public participation (Hanzl, 2007; Lee et al., 2023b; Ma et al., 2022). When transforming complex ideas into understandable formats, visualizations are found to be particularly helpful and have been seen as the only common language to all participants (King et al., 1989; Metze, 2020). For instance, 3D models, simulations, and XR are common digital visualization techniques.

Soman et al. (2024) identified XR as a motivational tool for engaging citizens, communities, and professionals in circular economy design and decision-making, as these technologies facilitate visualization and comprehension of complex concepts. Numerous researchers have investigated the potential of using VR and AR to overcome challenges in public engagement, showing encouraging results (Goudarznia et al., 2017; Hassan et al., 2025; Katika et al., 2022; Lee et al., 2024; Sabitha et al., 2024; Sermet and Demir, 2020). Katika et al. (2022) developed a mobile AR-based application that incorporates digital content relevant to circular economy concepts to engage the public, demonstrating a positive impact on citizens' interest and confidence in the circular economy, particularly among those with limited prior knowledge. Similarly, Goudarznia et al. (2017) examined AR's effectiveness in public participation for urban planning, highlighting its capability of to foster interactive decision-making processes that empower citizens. Extending AR's application beyond planning, Nadeem et al. (2025) proposed a framework of measuring using AR in marketing to improve climate-positive consumer engagement in sustainability. Lee et al., (2024) further explored how AR can enhance public participation in sustainable building systems, while Hunter et al. (2022) emphasized AR's value in enabling users to participate in sustainable urban planning, thereby increasing community engagement.

Sermet and Demir (2020) presented various AR and VR applications in environmental education, including several case studies that highlight the capacity of these technologies to raise awareness. Other studies have focused specifically on VR. For example, O'Grady et al. (2021) employed a gamified VR environment based on digital twin to provide immersive learning experiences of circular economy principles within the construction industry. Similarly, Spadoni et al. (2024) developed a VR experience that visualizes the environmental impacts of the fashion industry to promote awareness, while Etto et al. (2025) introduced a VR escape room game designed to enhance waste-sorting knowledge and practical skills, demonstrating greater effectiveness than traditional teaching methods. Similarly, Esmaeili and Thwaites (2021) created a VR game that immerses users in the environmental consequences of human activities aligned with the linear economy model, fostering a deeper sense of environmental urgency and awareness. Furthermore, Chen et al. (2021) illustrated how VR can be utilized to minimize the environmental impact of manufacturing processes. Scurati et al. (2021) proposed a design framework for developing VR experiences that promote sustainable behaviour by addressing emotional, rational, and practical dimensions. Nouri and Bouzaabia (2025) examined the impact of VR on users' perceptions of climate change, demonstrating its effectiveness in capturing attention and raising awareness.

Although research interest has surged in the field of MR technology (Carbonari et al., 2022; Holly et al., 2022; Stothard et al., 2019; Thiede et al., 2022), using MR as a tool for fostering awareness of circular economy principles remains underexplored. Several researchers have begun to bridge this gap. For instance, Zaharie et al. (2020) proposed VR and MR as an advanced educational methodology for the complex, multidisciplinary domain of the circular bioeconomy. More recently, studies in the related field of sustainability education has shown MR's effectiveness in enhancing STEM learning and user engagement (Criollo-C et al., 2025; Liu and Liu, 2025). Cao et al., (2024) The use of MR in education incorporates the benefits of AR and VR, which potentially amplifies user engagement and clarifies the often-complex ideas inherent in the circular economy. MR offers an opportunity for a personalized and interactive learning path, allowing users to engage with content in ways traditional educational methods cannot match. Recognizing the potential of MR, the authors aim to evaluate its effectiveness in improving the learning experience and elevating public awareness of circular economy principles in water systems.

3. RESEARCH METHODOLOGY

3.1 Experimental design

In this study, the authors presented a workflow to evaluate the effectiveness of MR as a learning tool. The primary objective was to determine if MR enhances knowledge acquisition and provides a more engaging experience compared to traditional teaching methods. The authors recruited 50 engineering students from a university in the United States Southern region. This group was specifically chosen not as a representation of the general public, but as a group of potential future engineering professionals whose perspectives and learning outcomes are relevant to the implementation of circular economy principles. These students were randomly assigned to two groups: a treatment group (n=25) and a control group (n=25). The treatment group used Microsoft® HoloLens 2 to interact with the learning content. The control group learned by watching traditional lecture videos. This design allowed for a direct comparison of the effectiveness of MR technology versus conventional lectures in circular economy education. The primary workflow was structured into four key steps: (1) Learning Materials Development, (2) Pre-activity Assessment, (3) Learning Activity, and (4) Post-activity Assessment. Each of these steps is described as follows:

(1) Learning Materials Development

The learning materials designated for the treatment group was an MR application on Microsoft® HoloLens 2, while the control group utilized a pre-recorded lecture video. The authors have detailed the development workflow for the MR application in previous publication (Lee and Leite, 2024). In this study, Autodesk® Navisworks, Autodesk® Infraworks, and Autodesk® 3DS Max were utilized for 3D model creation and optimization (Figure 1). Then, Unity® was used for developing and testing the MR application, which guides users through interactive elements and can be completed in approximately ten minutes. Specifically, the educational content focused on "hard-to-imagine" concepts, using a 3D model of the Seaholm Power Plant redevelopment project in Austin, TX, which served as a representative case study. The MR application enabled users to examine the intricate and otherwise "invisible" underground circular water system. For example, users could spatially position the 3D city model within their physical environment, manipulate its orientation to "see through" the ground plane and reveal the concealed infrastructure (e.g., piping and tanks) by moving the digital object, and interactively trace abstract resource flows, such as rainwater harvesting.

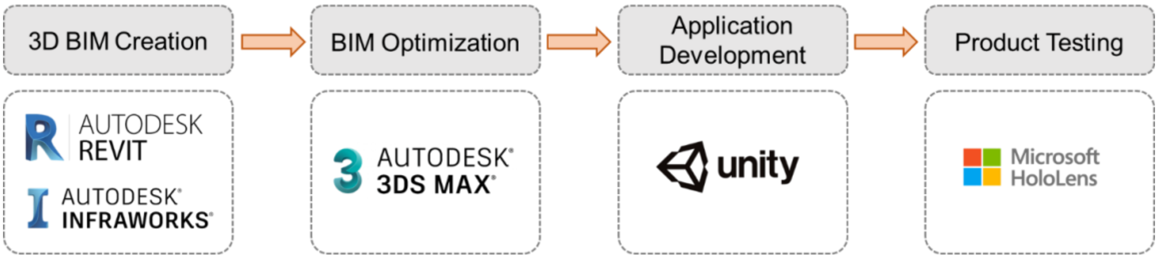

Figure 1: MR model preparation workflow (Lee and Leite, 2024).

For the control group, the lecture video was created using slides and artificial intelligence (AI) narration, culminating in a 10-minute video. To ensure content equivalency, the video extended beyond static visuals by incorporating pre-recorded animations and fly-throughs of the identical 3D models (e.g., the Seaholm project) utilized in the MR application. This method ensured both groups were exposed to the same "hard-to-imagine" concepts, such as the underground infrastructure. It is noteworthy that the MR application and the lecture video deliver the same educational content; the distinction lies solely in their respective methods of delivery.

(2) Pre-activity Assessment

The researchers used an online Qualtrics survey to collect participant demographic information and assess their initial knowledge. The survey also included questions about participants' prior experience with VR, MR, gaming, and their general computer skills to gauge their technological proficiency. In the knowledge test, students were prompted to answer ten fundamental multiple-choice questions concerning the circular economy in water systems, serving as a baseline measure of their understanding. Each correct answer earned one point, with a maximum of ten points. The knowledge test allowed a total of five minutes for completion, ensuring a swift yet effective assessment. The results from this pre-activity assessment would later provide valuable insights into the educational impact of the MR application and lecture video.

(3) Learning Activity

During the learning activity, students in the treatment group acquired knowledge of circular economy concepts through experiencing the MR application on Microsoft® HoloLens 2. This MR module was designed to be completed within ten minutes, incorporating interactions and educational content (Figure 2). In contrast, the control group participants spent ten minutes watching a lecture video on a laptop. This video, which featured slides and AI narration, delivered the exact same educational content as the MR application, ensuring the delivery method was the only variable.

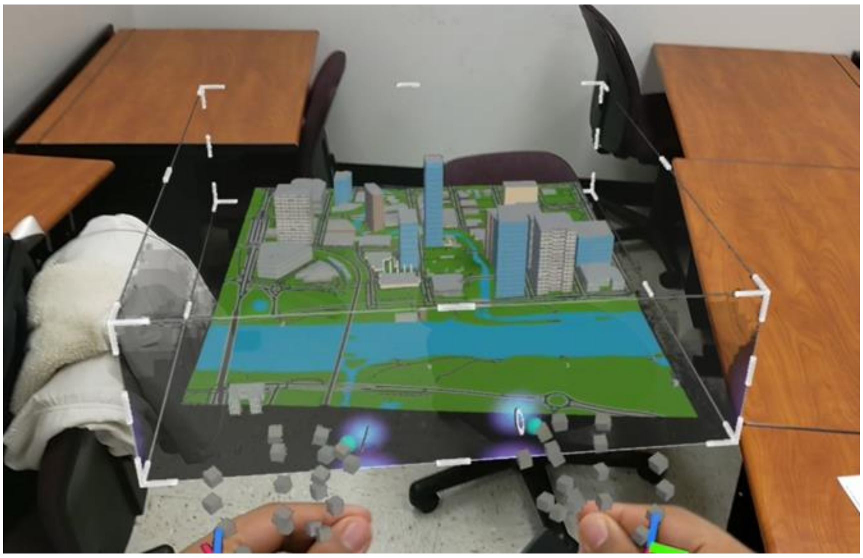

Figure 2 : MR Application Demonstration.

(4) Post-activity Assessment

The post-activity evaluation included the same set of knowledge-based questions as in the pre-activity assessment to quantify the knowledge acquisition and understanding. The scoring range remained from zero to ten points. Additionally, participants in the treatment group completed a series of questions regarding their experience with Microsoft® HoloLens 2. This feedback was intended to capture their perspectives, the usability of the technology, and its potential as a educational tool. The information gathered from these answers is crucial for assessing how engaging MR technology is and how it affects education in comparison to traditional learning methods.

3.2 Learning outcomes

The learning activity was designed to introduce foundational circular economy concepts in water systems using the Seaholm Power Plant case study. Given the short duration of the module, the intended learning outcomes focused on basic conceptual understanding rather than advanced engineering competencies. After completing the activity, students were expected to:

(1) Recognize the main components of the circular water system, including collection, treatment, storage, and reuse.

(2) Describe the basic flow of water through the circular system, such as how rainwater is collected, treated, and reused.

(3) Identify the key differences between linear and circular economy systems, including the primary advantages and limitations.

(4) Understand how MR visualization represents otherwise invisible system elements, such as underground infrastructure and resource flows.

These outcomes align with the introductory scope of the activity and reflect the level of understanding expected within a brief, 10-minute learning experience.

4. RESULTS AND DISCUSSION

4.1 Composition of participants

Figure 3 illustrates the educational levels of participants in each group. PhD students made up the largest portion of both groups, representing 52% of the control group and 40% of the treatment group. Undergraduate students, on the other hand, represent the smallest portion in each group, accounting for 20% in the control group and 24% in the treatment group.

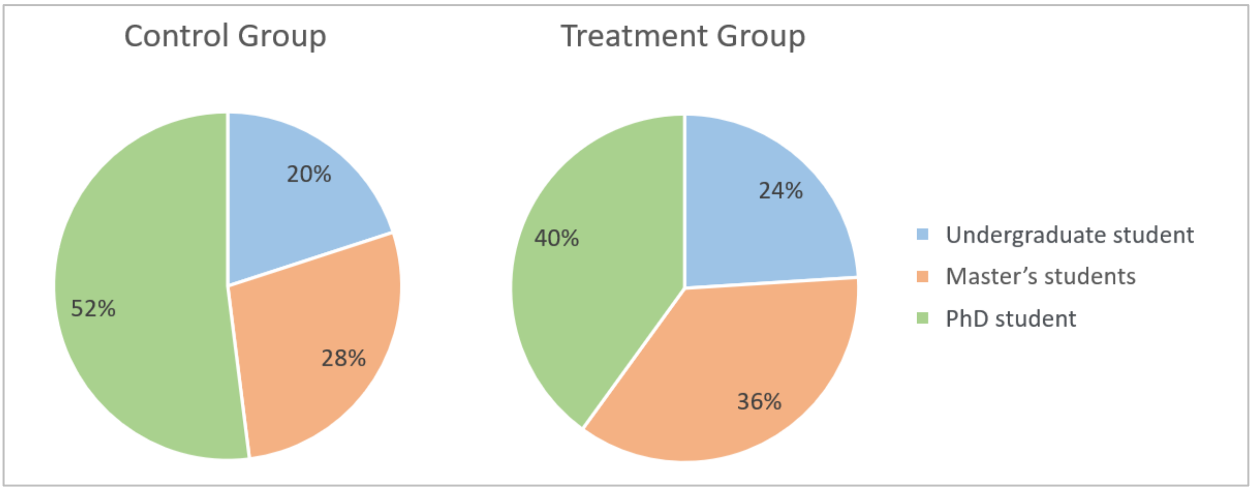

Figure 3: Educational levels of participants in each group.

4.2 Assessment scores for each group

Figure 4 shows the average pre- and post-activity evaluation scores for both groups, calculated as arithmetic mean values. The scores range from zero to ten, reflecting the group's overall performance and understanding of circular economy concepts before and after the learning activity. For the control group, the mean pre-score was 6.43, with a standard deviation of 0.95. The mean post-score was approximately 7.17 with a standard deviation of 1.15, resulting in an improvement of 11.5%. On the other hand, the mean pre and post-activity assessment scores of the treatment group was 6.64 (standard deviation = 1.05) and 8.44 (standard deviation = 1.26), respectively. The results indicate a more substantial improvement of 27.1%.

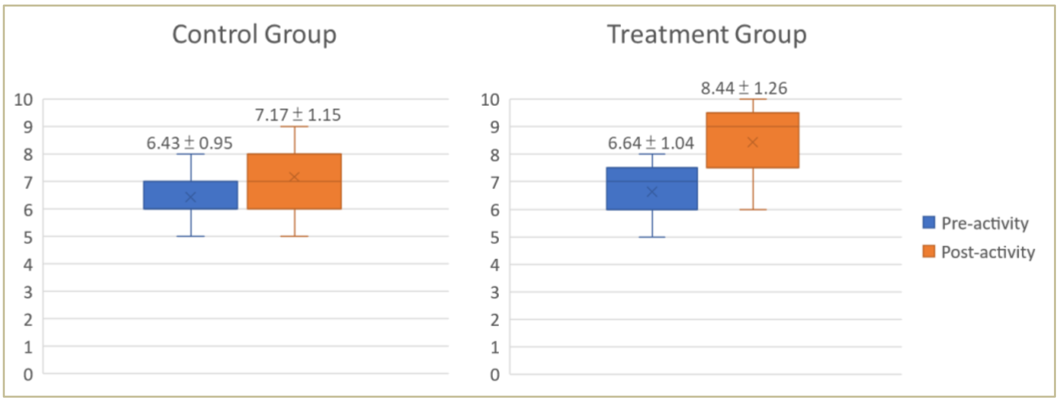

Figure 4 : Pre- and Post-activity Assessment Scores.

Figure 5 and Figure 6 demonstrate the individual score differences for each participant within the control and treatment groups, respectively. The score difference is calculated by subtracting the pre-activity score from the post-activity score for each participant. As shown in Figure 5, score differences of participants in the control group range from a decrease of 1 point to an increase of 3 points, indicating varied levels of improvement or decline. The majority of participants in this group show a positive difference, suggesting an overall improvement in the assessment scores after the activity (i.e., watching a lecture video). The score differences in the treatment group range from -1 to 6 (Figure 6). Furthermore, the treatment group displays a larger number of participants with higher positive score differences, indicating a more significant improvement after the activity (i.e., MR experience) for most participants compared to the control group.

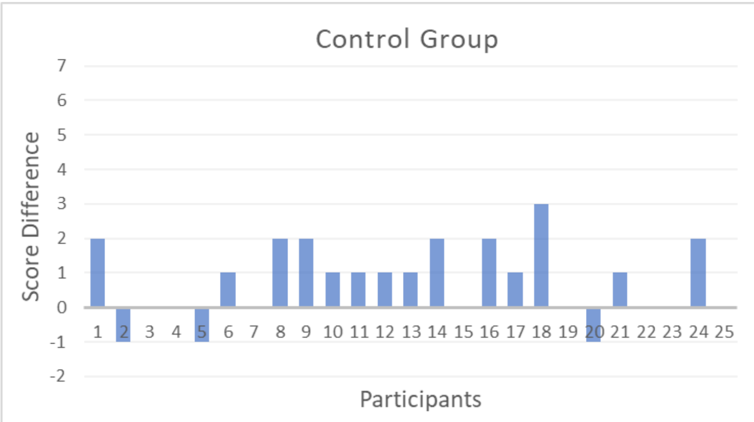

Figure 5 : Individual Score Differences in the Control Group.

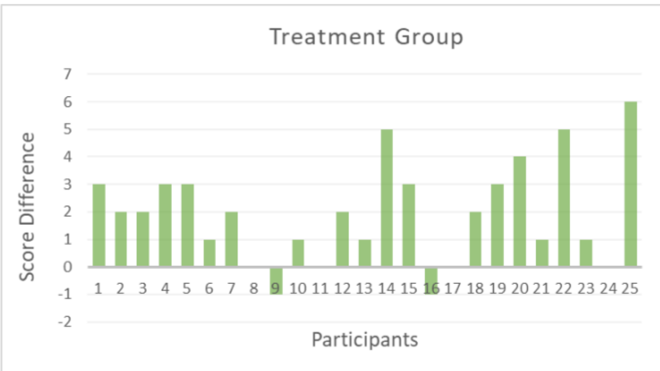

Figure 6: Individual Score Differences in the Treatment Group.

4.3 Within-group comparisons

In this study, the authors conducted experiments under the assumption that participant data follows a normal distribution. A paired t-test for within-group comparisons is conducted using pre- and post-activity scores in each group. The null hypothesis (H_0) was that there was no significant difference in terms of learning effectiveness before and after the intervention, namely watching lecture videos or using HoloLens 2. The alternative hypothesis (H_1) suggested a significant difference in learning effectiveness, with the post-activity scores being lower or higher than the pre-intervention scores, demonstrating an effect resulting from the intervention. In this study, a 5% significance level (α=0.05) was selected as the threshold for statistical significance.

The paired t-test on the control group yielded a statistic of 3.23 with a p-value of 0.0038. The p-value of the control group is less than 0.05, which indicates that the increase in scores from pre-test to post-test is statistically significant. Similarly, the paired t-test within the treatment group demonstrated a statistic of 5.9 with a p-value of 0.0052, indicating a statistically significant improvement in scores after the learning activity. Both groups showed improvement in their average assessment scores following the activity. Initially, the pre-activity scores were similar, with the control group at 6.43 and the treatment group slightly higher at 6.63. After the activity, the treatment group's score increased significantly to 8.46, indicating a substantial improvement (1.83) in knowledge due to the specific learning method employed. The control group's post-activity score also rose to 7.17, suggesting an improvement (0.74) but not as significant as the treatment group.

4.4 Independent samples t-test

In this research, the authors aim to compare the effectiveness of two distinct learning approaches: using HoloLens 2 and watching lecture videos. To validate the efficacy of the two learning experiences, an independent samples t-test was employed, which is particularly appropriate for comparing two independent groups. The independent samples t-test help determine the observed difference in post-activity and pre-activity assessment scores between the two groups are statistically significant, or if they could have occurred by chance. For independent samples t-test, the null Hypothesis (H_0) posited that there is no significant difference in the learning effectiveness between using HoloLens 2 and watching videos. Alternative Hypothesis (H_1): Learning with HoloLens 2 is more effective than learning through video lectures. A 5% significance level (α=0.05) was selected to determine the threshold for statistical significance in this research.

The independent t-test comparing the two learning approaches yielded a t-statistic of 2.71, and the p-value was found to be less than 0.05 (p-value = 0.0094) from the result of this study, suggesting there is a statistically significant difference between the treatment and control groups in terms of scores. That is, the learning effectiveness of using HoloLens 2 differs from that of watching lecture video. Since the p-value is lower than the predetermined threshold of α=0.05, we reject the null hypothesis that assumed there are no difference in effectiveness. As a result, the findings from this study support the alternative hypothesis that learning with HoloLens 2 is indeed more effective than watching lecture videos in the context of circular economy in water systems.

4.5 Effect size calculation

Effect size calculation is a statistical measure that quantifies the magnitude of the difference between two groups, indicating how large the effect is. In education research, Cohen's d (Cohen, 1988) is one commonly used measure of effect size, which is especially helpful in comparing the difference between two means. Cohen's d is calculated as follows:

$$d = \frac{M_1 - M_2}{SD_{pooled}} \tag{1}$$

where M_1 = the mean value of the first group

M_2 = the mean value of the second group

SD_{pooled} = the pooled standard deviation of the two groups

The pooled standard deviation (SD_{pooled}) is a weighted average of the standard deviation of the two groups, which is calculated using the following formula:

$$SD_{pooled} = \sqrt{\frac{(n_1 - 1)SD_1{}^2 + (n_2 - 1)SD_2{}^2}{n_1 + n_2 - 2}} \tag{2}$$

where n_1 and n_2 represent the sample sizes, and SD_1 and SD_2 are the standard deviations for each group.

In educational research, Cohen's d values can be interpreted as follows: small effect: 0.2, medium effect: 0.5, and large effect: 0.8 (Cohen, 1988). The Cohen's d value for the experiment of this study is approximately 0.78, which is close to the threshold for a "large" effect. Therefore, it can be concluded that using HoloLens 2 had a substantial impact on learning experiences in comparison to traditional learning approach in this study.

4.6 Regression Analysis

In the pre-activity assessment, participants' demographic information such as ages, current academic status, and majors was collected. Furthermore, several self-rated relevant skills and experiences are recorded. Combining these data with test scores, the regression analysis was conducted based on Pearson correlation coefficients (r), which measure the linear relationship between two variables X and Y. The Pearson correlation coefficient ranges from -1 to 1, with -1 and 1 indicates perfect negative and positive linear relationships respectively. The r is calculated as follows:

$$r = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 \sum(Y_i - \bar{Y})^2}} \tag{3}$$

where X_i and Y_i are individual scores

$\bar{X}$ and $\bar{Y}$ are the means of X and Y

The regression analysis uncovers the following key findings, where a correlation heatmap is provided in Figure 7:

1. R-squared: The R-squared is 0.366, suggesting that approximately 36.6% of the variability in the post-activity assessment scores can be explained by the model. The remaining 63.4% of the variability is attributed to factors not measured in this study. These could include individual differences in motivation, learning styles, or specific prior knowledge not captured by the pre-test. While a portion of the score variability is accounted for, this suggests that the model has a moderate, but not perfect, predictive ability..
2. Experience with VR/MR headsets: The p-value of this variable is 0.034, indicating that participants' prior experience with VR or MR headsets is a predictor of post-activity assessment scores. This finding suggests that participants with previous exposure to this technology performed better. This advantage may stem from their comfort with the hardware and interface, allowing them to focus more on the educational content rather than the technology itself. Conversely, this added cognitive load from navigating an unfamiliar interface likely explains the few instances of score decreases observed in the treatment group (Figure 6), as these participants may have been more focused on the hardware than the lesson.
3. Age: The p-value of age variable is not statistically significant ($p = 0.166$), illustrating that age may not have a strong impact on the post-test scores.
4. Academic Background: Current academic status and major variables do not show statistical significance. Thus, within this sample, these variables may not have strong influence on the post-activity evaluation scores.

4.7 Perceived Quality

In the post-activity evaluation of this study, the authors employed a comprehensive multidimensional model, as suggested by Pribeanu et al. (2017), to assess the perceived quality of the MR application as a learning tool for circular economy concepts. The model focuses on three core aspects, including ergonomic quality (Q-ERG), learning quality(Q-EDU), and hedonic quality (Q-HED). Also, the model contains various constructs, such as Perceived Usefulness (PU), Perceived Efficiency (PEF), and Perceived Ease of Use (PEU). The post-activity survey was constructed based on the variables of this model, as shown in Table 1, using a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree) to collect participants' opinions.

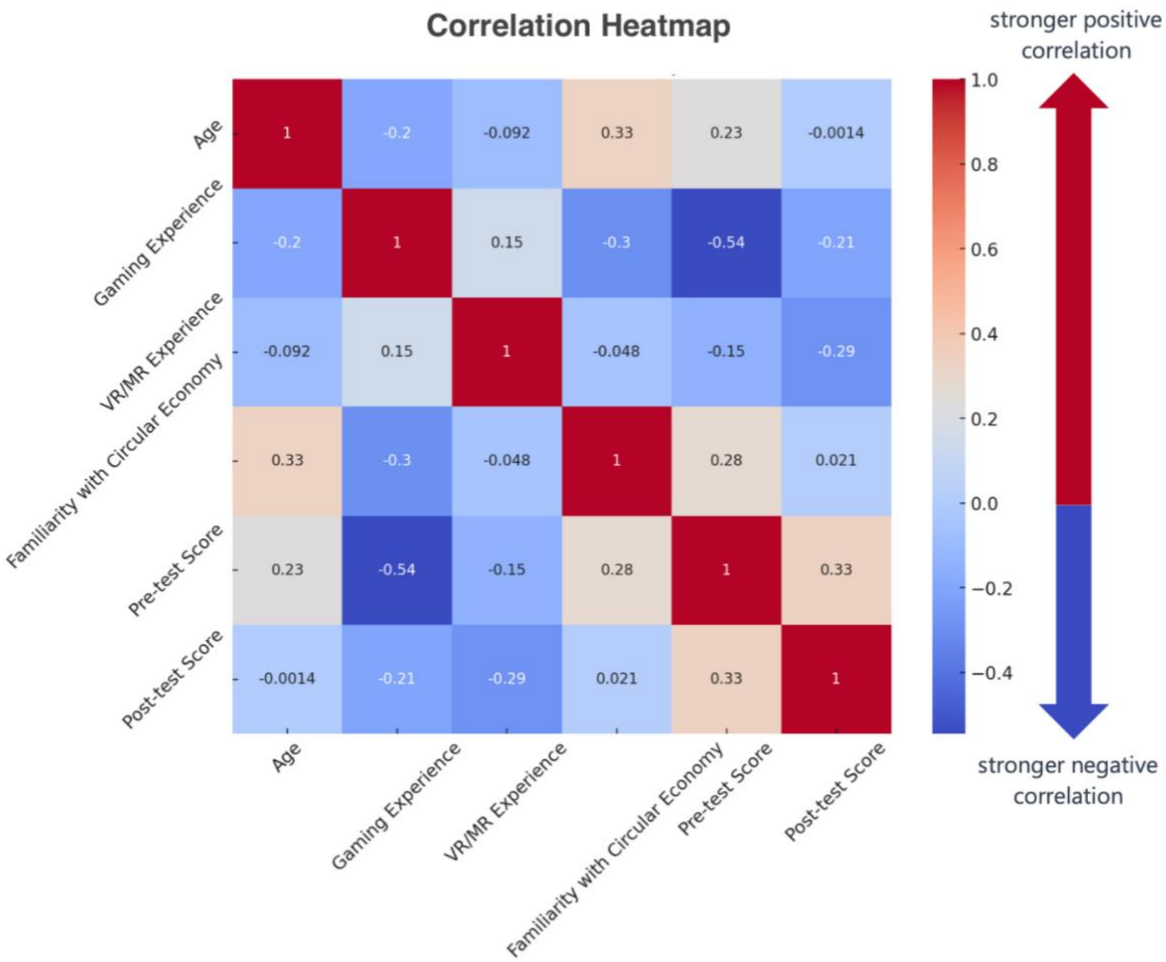

Figure 7 : Correlation Heatmap.

Table 1 : Aspects, constructs, items, and variables in this study.

Aspect	Construct	Item	Variable
Ergonomic quality(Q-ERG)	Perceived learnability (PEL)	PEL1	Understanding how to use Hololens2 is easy.
		PEL2	It would be easy to learn how to use HoloLens2.
		PEL3	It would be easy to remember how to use HoloLens2.
	Perceived ease of use (PEU)	PEU1	It would be easy to use HoloLens2 for learning Circular Economy/Sustainability.
		PEU2	Interacting with HoloLens2 was easy for me.
		PEU3	HoloLens2 is easy to use.
Learning quality(Q-EDU)	Perceived efficiency (PEF)	PEF1	HoloLens2 would help me to understand the lesson faster.
		PEF2	HoloLens2 would help me to learn more quickly.
		PEF3	HoloLens2 would help me to understand the lesson better.
	Perceived usefulness (PU)	PU1	After using HoloLens2 my Circular Economy/Sustainability knowledge will improve.
		PU2	HoloLens2 exercises are useful to test my knowledge.
		PU3	HoloLens2 helps learning Circular Economy/Sustainability.
Hedonic quality(Q-HED)	Perceived cognitive absorption (PCA)	PCA1	Time appeared to go by very quickly when I was using HoloLens2.
		PCA2	While using HoloLens2 I was absorbed in what I was doing.
		PCA3	While using HoloLens2 I was able to concentrate on the lesson.
	Perceived enjoyment (PE)	PE1	Using HoloLens2 is an enjoyable learning experience.
		PE2	I like learning Circular Economy/Sustainability with HoloLens2.
		PE3	I enjoyed using HoloLens2.

The authors performed data analysis through IBM SPSS Amos 26 Graphics, to evaluate reliability and validity. As shown in Table 2, all standardized factor loadings are larger than 0.7 (ranging from 0.701 to 0.975), indicating a strong correlation between items and their respective constructs. For each item, the composite reliability (CR) is above the threshold of 0.7, strengthening the internal consistency of the constructs. Furthermore, the average variance extracted (AVE) values, ranging from 0.529 to 0.782, also surpassed the minimum recommended level of 0.50. This confirms a robust relationship between the constructs and their items.

Table 2: Convergent validity, descriptive statistics, and construct reliability of this study.

Construct	Item	Mean	SD	R^2	Loading	t-Value	CR	AVE
PU	PU1	3.960	0.790	0.860	0.927	6.465	0.897	0.748
	PU2	3.800	0.957	0.492	0.701	4.231		
	PU3	3.960	0.841	0.893	0.945	-		
PEF	PEF1	3.600	1.190	0.752	0.802	4.788	0.914	0.782
	PEF2	3.600	1.118	0.951	0.867	5.016		
	PEF3	3.880	0.927	0.600	0.975	-		
PEU	PEU1	3.840	0.943	0.151	0.789	1.422	0.866	0.684
	PEU2	3.680	0.945	0.472	0.887	1.806		
	PEU3	3.680	0.988	0.904	0.802	-		
PEL	PEL1	3.840	0.850	0.155	0.794	2.218	0.818	0.599
	PEL2	4.040	1.060	0.824	0.793	1.766		
	PEL3	4.400	0.707	0.402	0.734	-		
PE	PE1	4.480	0.823	0.660	0.813	3.770	0.856	0.665
	PE2	4.240	0.926	0.781	0.883	3.822		
	PE3	4.360	0.810	0.554	0.745	-		
PCA	PCA1	4.040	0.935	0.074	0.721	1.819	0.771	0.529
	PCA2	3.920	1.187	2.350	0.733	1.674		
	PCA3	3.840	1.214	0.183	0.728	-		

In summary, the above analysis indicates that HoloLens 2 has been evaluated as a high-quality learning tool, as perceived by the participants. The MR experience scored well across various facets of quality, demonstrating its potential as an effective educational resource in the field of circular economy.

5. CONCLUSIONS

In response to the global water crisis, the concept of a circular economy has been advocated as a promising solution in recent decades, given its potential in establishing more sustainable water resource management. Although extensive research efforts have been made in this field, the challenge of conveying those works to the public is far from being settled. For the widespread adoption of circular economy principles in the water sector, it is essential to increase public awareness as it is often identified as one of the biggest barriers. Consequently, in this paper, the authors aimed to bridge the knowledge gap between the general public and circular economy principles in water systems through the latest visualization technology. Visualization technologies have the ability to simplify complex or abstract ideas into tangible formats, enabling users to easily digest without extensive prior knowledge or experience.

Among state-of-the-art visualization tools, mixed reality was selected as a learning tool in the study. The researchers proposed a methodology to validate the effectiveness of using MR to improve engineering students' learning experience in circular economy concepts in urban water systems. A series of experiments was conducted by recruiting engineering students from a certain university, focusing on investigating their learning outcomes. The 50 participants recruited were randomly assigned to the treatment and control groups. Results show that both groups have statistically significant improvement in their scores. Moreover, the results also suggested using HoloLens 2 had substantial impact on students' performance compared to watching a lecture video. This demonstrated the potential of MR in improving learning experience in circular economy concepts, simplifying hard-to-imagine concepts into engaging MR experience to connect the public and communicate with the broader audience.

A key limitation is that our findings, while significant for engineering education, cannot be generalized to the broader public. Our study focused on a group of potential future engineering professionals responsible for implementing circular economy, not the general population responsible for adopting it. To further advance and contribute to the field of study, future efforts will focus on expanding our participant pool to include a more diverse demographic, encompassing various majors and educational backgrounds. In this way, a more comprehensive understanding of the effectiveness of MR as a learning tool can be provided. The same methdology could also be replicated in other domains, such as the circular economy in energy systems, to further validate the impact of MR on engagement and education. Additionally, future research should integrate the detailed perceived quality metrics, such as Perceived Ease of Use (PEU) and ergonomic factors, directly into the regression models to better quantify the impact of cognitive load and interface friction on learning outcomes. Ultimately, by increasing understanding of these vital concepts, a greater adoption of circular economy concepts can be achieved, which is crucial for confronting environmental challenges.

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REFERENCES

Adami, P., Rodrigues, P.B., Woods, P.J., Becerik-Gerber, B., Soibelman, L., Copur-Gencturk, Y., Lucas, G., 2022. Impact of VR-Based Training on Human–Robot Interaction for Remote Operating Construction Robots. J. Comput. Civ. Eng. 36, 04022006. https://doi.org/10.1061/(ASCE)CP.1943-5487.0001016

Begout, P., Kubicki, S., Bricard, E., Duval, T., 2022. Augmented Reality Authoring of Digital Twins: Design, Implementation and Evaluation in an Industry 4.0 Context. Front. Virtual Real. 3. https://doi.org/10.3389/frvir.2022.918685

Billinghurst, M., Duenser, A., 2012. Augmented Reality in the Classroom. Computer 45, 56–63. https://doi.org/10.1109/MC.2012.111

Blomsma, F., Brennan, G., 2017. The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity. J. Ind. Ecol. 21, 603–614. https://doi.org/10.1111/jiec.12603

Bouziotas, D., van Duuren, D., van Alphen, H.-J., Frijns, J., Nikolopoulos, D., Makropoulos, C., 2019. Towards Circular Water Neighborhoods: Simulation-Based Decision Support for Integrated Decentralized Urban Water Systems. Water 11, 1227. https://doi.org/10.3390/w11061227

Cao, J., Liu, X., Su, X., Hædahl, J.E., Fjellestad, T.B., Haziri, D., Hoang-An Vu, A., Koskiaho, J., Karjalainen, S.M., Ronkanen, A., Tarkoma, S., Hui, P., 2024. Head-mounted display-based augmented reality for water quality visualisation. Water Sci. Eng. 17, 236–248. https://doi.org/10.1016/j.wse.2023.12.002

Carbonari, A., Franco, C., Naticchia, B., Spegni, F., Vaccarini, M., 2022. A Mixed Reality Application for the On-Site Assessment of Building Renovation: Development and Testing. Sustainability 14, 13239. https://doi.org/10.3390/su142013239

Chen, X., Gong, L., Berce, A., Johansson, B., Despeisse, M., 2021. Implications of Virtual Reality on Environmental Sustainability in Manufacturing Industry: A Case Study. Procedia CIRP, 54th CIRP CMS 2021 - Towards Digitalized Manufacturing 4.0 104, 464–469. https://doi.org/10.1016/j.procir.2021.11.078

Cheng, C.-S., Luo, L., Murphy, S., Lee, Y.-C., Leite, F., 2024. A framework to enhance disaster debris estimation with AI and aerial photogrammetry. Int. J. Disaster Risk Reduct. 107, 104468. https://doi.org/10.1016/j.ijdrr.2024.104468

Cheng, J.-Y., Gheisari, M., Jeelani, I., 2023. Using 360-Degree Virtual Reality Technology for Training Construction Workers about Safety Challenges of Drones. J. Comput. Civ. Eng. 37, 04023018. https://doi.org/10.1061/JCCEE5.CPENG-5140

Cohen, J., 1988. Statistical power analysis for the behavioral sciences, 2nd ed. ed. L. Erlbaum Associates, Hillsdale, N.J.

Criollo-C, S., Guerrero-Arias, A., Jaramillo-Alcázar, A., Luján-Mora, S., 2025. Using Mixed Reality (MR) as an Emerging Technology for Improving Higher Education: Analysis of Mental Workload. Emerg. Sci. J. 8, 410–424. https://doi.org/10.28991/ESJ-2024-SIED1-024

Dodevska, M., Zdravevski, E., Chorbev, I., Kostoska, M., Branco, F., Coelho, P.J., Pires, I.M., Lameski, P., 2025. Virtual reality as a learning tool: Evaluating the use and effectiveness of simulation laboratories in educational settings. Soc. Sci. Humanit. Open 12, 101742. https://doi.org/10.1016/j.ssaho.2025.101742

Eshetu Moges, M., Todt, D., Heistad, A., 2018. Treatment of Source-Separated Blackwater: A Decentralized Strategy for Nutrient Recovery towards a Circular Economy. Water 10, 463. https://doi.org/10.3390/w10040463

Esmaeili, H., Thwaites, H., 2021. Addressing environmental awareness through immersive VR experiences, gamification and hypothetical scenario development. Virtual Creat. 11, 223–236. https://doi.org/10.1386/vcr_00049_1

Etto, J., Hurtig, K., Ivanov, P., Gong, Z., Colley, A., Häkkilä, J., 2025. Gamified Sustainability: Virtual Reality Escape Room for Recycling Education, in: 2025 IEEE International Conference on Multimedia and Expo Workshops (ICMEW). Presented at the 2025 IEEE International Conference on Multimedia and Expo Workshops (ICMEW), pp. 1–2. https://doi.org/10.1109/ICMEW68306.2025.11152077

Gleason Espíndola, J.A., Cordova, F., Casiano Flores, C., 2018. The importance of urban rainwater harvesting in circular economy: the case of Guadalajara city. Manag. Res. Rev. 41, 533–553. https://doi.org/10.1108/MRR-02-2018-0064

Goudarznia, T., Pietsch, M., Krug, R., 2017. Testing the Effectiveness of Augmented Reality in the Public Participation Process: A Case Study in the City of Bernburg. Wichmann Verlag, DE.

Guerra, B.C., Leite, F., 2021. Circular economy in the construction industry: An overview of United States stakeholders' awareness, major challenges, and enablers. Resour. Conserv. Recycl. 170, 105617. https://doi.org/10.1016/j.resconrec.2021.105617

Hanzl, M., 2007. Information technology as a tool for public participation in urban planning: a review of experiments and potentials. Des. Stud., Participatory Design 28, 289–307. https://doi.org/10.1016/j.destud.2007.02.003

Hassan, N.H., Rahim, N.A.A., Hoong, A.L.S., Mostafa, K., 2025. A Conceptual Study on Utilization of Artificial Intelligence (AI), Virtual Reality (VR) and Augmented Reality (AR) on Green Education: Effectiveness and Engagement, in: Chen, W., PP Abdul Majeed, A., Ping Tan, A.H., Zhang, F., Yan, Y., Luo, Y., Huang, L., Liu, C., Zhu, Y. (Eds.), Selected Proceedings from the 2nd International Conference on Intelligent Manufacturing and Robotics, ICIMR 2024, 22-23 August, Suzhou, China. Springer Nature, Singapore, pp. 270–278. https://doi.org/10.1007/978-981-96-3949-6_20

Holly, F., Zigart, T., Maurer, M., Wolfartsberger, J., Brunnhofer, M., Sorko, S.R., Moser, T., Schlager, A., 2022. Gaining Impact with Mixed Reality in Industry – A Sustainable Approach, in: Proceedings of the 2022 8th International Conference on Computer Technology Applications, ICCTA '22. Association for Computing Machinery, New York, NY, USA, pp. 128–134. https://doi.org/10.1145/3543712.3543729

Hunter, M.G., Soro, A., Brown, R.A., Harman, J., Yigitcanlar, T., 2022. Augmenting Community Engagement in City 4.0: Considerations for Digital Agency in Urban Public Space. Sustainability 14, 9803. https://doi.org/10.3390/su14169803

Katika, T., Karaseitanidis, I., Tsiakou, D., Makropoulos, C., Amditis, A., 2022. Augmented Reality (AR) Supporting Citizen Engagement in Circular Economy. Circ. Econ. Sustain. 2, 1077–1104. https://doi.org/10.1007/s43615-021-00137-7

King, S., Conley, M., Bill, L., Drew, F., 1989. Co-design: A Process of Design Participation.

Lee, Y.-C., Alsuhaibani, A., Cheng, C.-S., Leite, F., 2024. Enhancing Public Engagement in Sustainable Systems through Augmented Reality. Int. Symp. Autom. Robot. Constr. ISARC Proc. 2024 Proceedings of the 41st ISARC, Lille, France, 593–598. https://doi.org/10.22260/ISARC2024/0077

Lee, Y.-C., Leite, F., 2024. Mixed Reality Promoting Circular Economy in Urban Water Systems, in: Computing in Civil Engineering 2023. Presented at the ASCE International Conference on Computing in Civil Engineering, American Society of Civil Engineers, Corvallis, Oregon, U.S.A, pp. 102–109. https://doi.org/10.1061/9780784485248.013

Lee, Y.-C., Leite, F., Lieberknecht, K., 2023a. Prioritizing selection criteria of distributed circular water systems: A fuzzy based multi-criteria decision-making approach. J. Clean. Prod. 417, 138073. https://doi.org/10.1016/j.jclepro.2023.138073

Lee, Y.-C., Ma, J.W., Leite, F., 2023b. A parametric approach towards semi-automated 3D as-built modeling. J. Inf. Technol. Constr. ITcon 28, 806–825. https://doi.org/10.36680/j.itcon.2023.041

Liu, Yu, Liu, Yue, 2025. Advancing STEM Education for Sustainability: The Impact of Graphical Knowledge Visualization and User Experience on Continuance Intention in Mixed-Reality Environments. Sustainability 17, 3869. https://doi.org/10.3390/su17093869

Ma, J.W., Lee, Y.-C., Leite, F., 2022. A Practical Application Using Parametric Modeling for As-Built BIM Generation from Point Clouds, in: Construction Research Congress 2022. pp. 830–838. https://doi.org/10.1061/9780784483961.087

Makropoulos, C., Rozos, E., Tsoukalas, I., Plevri, A., Karakatsanis, G., Karagiannidis, L., Makri, E., Lioumis, C., Noutsopoulos, C., Mamais, D., Rippis, C., Lytras, E., 2018. Sewer-mining: A water reuse option supporting circular economy, public service provision and entrepreneurship. J. Environ. Manage., Sustainable waste and wastewater management 216, 285–298. https://doi.org/10.1016/j.jenvman.2017.07.026

Metze, T., 2020. Visualization in environmental policy and planning: a systematic review and research agenda. J. Environ. Policy Plan. 22, 745–760. https://doi.org/10.1080/1523908X.2020.1798751

Morseletto, P., 2020. Targets for a circular economy. Resour. Conserv. Recycl. 153, 104553. https://doi.org/10.1016/j.resconrec.2019.104553

Nadeem, W., Ashraf, A.R., Kumar, V., 2025. Fostering consumer engagement with sustainability marketing using augmented reality (SMART): A climate change response. J. Bus. Res. 192, 115289. https://doi.org/10.1016/j.jbusres.2025.115289

Negrão, M.D., Maciel, A., 2024. Characterizing head-gaze and hand affordances using AR for laparoscopy. Comput. Graph. 121, 103936. https://doi.org/10.1016/j.cag.2024.103936

Nouri, I., Bouzaabia, R., 2025. Impact of immersive virtual reality on environmental mental imagery, climate risk perception and attitudes towards mitigation behaviors. Eur. J. Sustain. Dev. Res. 9, em0331. https://doi.org/10.29333/ejosdr/16833

O'Grady, T.M., Brajkovich, N., Minunno, R., Chong, H.-Y., Morrison, G.M., 2021. Circular Economy and Virtual Reality in Advanced BIM-Based Prefabricated Construction. Energies 14, 4065. https://doi.org/10.3390/en14134065

Ogunseiju, O., Akinniyi, A., Gonsalves, N., Khalid, M., Akanmu, A., 2023. Detecting Learning Stages within a Sensor-Based Mixed Reality Learning Environment Using Deep Learning. J. Comput. Civ. Eng. 37, 04023011. https://doi.org/10.1061/JCCEE5.CPENG-5169

Papaefthymiou, S., Giannakopoulos, A., Roussos, P., Kourtesis, P., 2024. Mitigating Cybersickness in Virtual Reality: Impact of Eye–Hand Coordination Tasks, Immersion, and Gaming Skills. Virtual Worlds 3, 506–535. https://doi.org/10.3390/virtualworlds3040027

Pribeanu, C., Balog, A., Iordache, D.D., 2017. Measuring the perceived quality of an AR-based learning application: a multidimensional model. Interact. Learn. Environ. 25, 482–495. https://doi.org/10.1080/10494820.2016.1143375

Quintero, J., Baldiris, S., Rubira, R., Cerón, J., Velez, G., 2019. Augmented Reality in Educational Inclusion. A Systematic Review on the Last Decade. Front. Psychol. 10.

Radu, I., 2014. Augmented reality in education: a meta-review and cross-media analysis. Pers. Ubiquitous Comput 18, 1533–1543. https://doi.org/10.1007/s00779-013-0747-y

Roest, K., Smeets, P., Zwertvaegher, A., Cortial, H., van Odijk, S., Klaversma, E., 2016. Applicability of decentralized versus centralized drinking water production and wastewater treatment in an office park as example of a sustainable circular economy in Amsterdam, the Netherlands. Eng. Manag. 10.

Sabitha, R., Selvaraj, G., Yuvaraj, S., M, G., Rajendrean, B., Murugan, S., 2024. Augmented Reality for Public Engagement in Sustainable City Planning: Cloud and Machine Learning Integration. https://doi.org/10.1109/AMATHE61652.2024.10582095

Sakib, M.N., Chaspari, T., Behzadan, A.H., 2021. Physiological Data Models to Understand the Effectiveness of Drone Operation Training in Immersive Virtual Reality. J. Comput. Civ. Eng. 35, 04020053. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000941

Scurati, G.W., Bertoni, M., Graziosi, S., Ferrise, F., 2021. Exploring the Use of Virtual Reality to Support Environmentally Sustainable Behavior: A Framework to Design Experiences. Sustainability 13, 943. https://doi.org/10.3390/su13020943

Sermet, Y., Demir, I., 2020. Virtual and Augmented Reality Applications for Environmental Science Education and Training. https://doi.org/10.4324/9781003001874-17

Skaaland, E., Pitera, K., 2021. Investigating the use of visualization to improve public participation in infrastructure projects: how are digital approaches used and what value do they bring? Urban Plan. Transp. Res. 9, 171–185. https://doi.org/10.1080/21650020.2021.1887757

Smol, M., Adam, C., Preisner, M., 2020. Circular economy model framework in the European water and wastewater sector. J. Mater. Cycles Waste Manag. 22, 682–697. https://doi.org/10.1007/s10163-019-00960-z

Soman, R.K., Nikolić, D., Sanchez, B., 2024. Extended Reality as a Catalyst for Circular Economy Transition in the Built Environment, in: De Wolf, C., Çetin, S., Bocken, N.M.P. (Eds.), A Circular Built Environment in the Digital Age. Springer International Publishing, Cham, pp. 171–193. https://doi.org/10.1007/978-3-031-39675-5_10

Spadoni, E., Fiocca, A., Zoni, G., Infante, L.M.U., Cerutti, L., Maccarrone, P., Carulli, M., Bordegoni, M., 2024. A virtual reality experience to raise sustainability awareness within the fashion industry. Proc. Des. Soc. 4, 1447–1456. https://doi.org/10.1017/pds.2024.147

Stothard, P., Squelch, A., Stone, R., Van Wyk, E., 2019. Towards sustainable mixed reality simulation for the mining industry. Min. Technol. 128, 246–254. https://doi.org/10.1080/25726668.2019.1645519

The World Bank, 2021. Water in Circular Economy and Resilience.

Thiede, S., Damgrave, R., Lutters, E., 2022. Mixed reality towards environmentally sustainable manufacturing – overview, barriers and design recommendations. Procedia CIRP, The 29th CIRP Conference on Life Cycle Engineering, April 4 – 6, 2022, Leuven, Belgium. 105, 308–313. https://doi.org/10.1016/j.procir.2022.02.051

World Economic Forum, 2021. The Global Risks Report 2021.

World Health Organization, United Nations Children's Fund, 2021. Progress on household drinking water, sanitation and hygiene, 2000-2020: Five years into the SDGs.

Zaharie, M.G., Caramihai, M., Adroguer, M., Blánquez, P., Kuppens, T., Radu, N., 2020. Virtual Reality and Mixed Reality Education: A Solution for Today's Education in a Circular Bioeconomy. Proceedings 57, 37. https://doi.org/10.3390/proceedings2020057037