Can Virtual Reality Help Build a More Sustainable Construction Industry?

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Abstract

The construction industry is under increasing pressure to reduce carbon emissions, improve productivity, and adopt more sustainable building practices. However, the implementation of emerging technologies such as 3D printing with raw earth materials remains constrained by limited workforce readiness, insufficient practical training, and persistent gaps between theoretical knowledge and applied skills. This study investigates the potential of Virtual Reality (VR) to address these challenges through the development and evaluation of EcoPrint VR, an immersive training platform designed to simulate 3D printing processes using earth-based materials. Drawing on a mixed-methods research design and guided by Kirkpatrick's Four-Level Training Evaluation Model, the study examines current sustainable construction training challenges, the design of the VR learning environment, and user outcomes following participation in VR training sessions. The findings indicate that VR-based training can substantially improve practical confidence and understanding, with confidence in operating 3D printing equipment increasing by 85% and confidence in material preparation increasing by 76%. Participants also reported that the immersive environment provided a safe, interactive, and engaging space for practicing complex procedures. The study further suggests that VR-based training can reduce training costs, minimise material waste, and support wider adoption of sustainable construction practices. At the same time, it identifies areas requiring refinement, including user comfort and the need for more structured instructional guidance. The article concludes that immersive training technologies can play a significant role in preparing the construction workforce for the transition toward low-carbon, digitally enabled construction.

Keywords: virtual reality, sustainable construction, raw earth construction, 3D printing, immersive learning, workforce training, EcoPrint VR.

1. Introduction

The construction industry occupies a critical position within global sustainability debates because of its significant environmental footprint and its central role in shaping the built environment. The sector accounts for approximately 39% of global energy-related carbon emissions, making it one of the largest contributors to environmental degradation and a key target for low-carbon transition strategies (Nshimiyimana et al., 2021). Although sustainable construction methods have advanced considerably in recent years, their uptake remains constrained by practical barriers including technical knowledge gaps, implementation costs, and shortages of appropriately trained personnel (Abotaleb et al., 2022; Billings, 2023). These barriers are particularly visible in the adoption of new construction methods such as 3D printing with raw earth materials, where industry participants often lack both familiarity and confidence in applying the technology in real-world settings.

Emerging technologies offer considerable promise in responding to these challenges. Additive manufacturing methods have introduced new possibilities for reducing material waste, improving precision, and enabling more efficient construction workflows (Puzatova et al., 2022). At the same time, raw earth materials have gained renewed attention as low-impact alternatives to conventional construction materials because of their low embodied energy, recyclability, local availability, and thermal performance advantages (Parlato et al., 2023; Gomaa et al., 2022). These developments suggest that the convergence of sustainable materials and digital fabrication could support a meaningful transformation in the construction sector. However, the benefits of these innovations cannot be fully realised unless the workforce is prepared to understand, operate, and implement them effectively.

Training remains a central challenge in this respect. Traditional teaching methods often struggle to provide learners with meaningful practical exposure to advanced equipment, material systems, and construction workflows, especially where equipment is expensive, access is limited, or safety concerns are present (Billings, 2023; Losini et al., 2021). As a result, there is a growing need for alternative training strategies that can bridge the divide between theoretical understanding and applied competence. Virtual reality (VR) has emerged as one such strategy. By enabling immersive, interactive, and repeatable simulation, VR can create risk-free learning environments in which users develop both procedural understanding and practical confidence (Wang et al., 2018; Getuli et al., 2023). This article explores that potential through the case of EcoPrint VR, a VR training platform developed to support 3D printing with earth materials in sustainable construction contexts.

The purpose of this article is to examine whether VR can help build a more sustainable construction industry by improving training effectiveness and workforce readiness for emerging construction technologies. The article presents the context for the study, reviews the relevant literature, outlines the methodology used in developing and evaluating EcoPrint VR, reports the principal findings, and discusses their implications for sustainable construction education and practice. In doing so, it contributes to current debates on how digital tools can support environmentally responsible and skills-responsive innovation in the construction sector.

2. Literature Review

2.1 Raw Earth Construction and Sustainability

Raw earth construction has a long and well-documented history, with traditional methods such as rammed earth, adobe, and cob continuing to attract attention in contemporary sustainability research. These construction methods rely on naturally available materials that typically require less industrial processing than conventional materials, thereby reducing energy consumption and transport-related emissions (Mendes et al., 2018; Quagliarini et al., 2010). The enduring performance of these techniques, along with their adaptability across climates and regions, supports their relevance to modern low-impact building strategies. In the source study, these traditions are visually represented through Figure 1 (rammed earth construction), Figure 2 (adobe construction), and Figure 3 (cob construction), each illustrating established forms of earth-based building practice.

Figure 1: Rammed earth home on the Kapiti (Source: EBANZ)

Figure 2: A light adobe house at the beginning of construction (Source: EBANZ)

Figure 3: Broadgreen House in Nelson (Source: EBANZ)

The environmental advantages of raw earth materials are substantial. Research synthesised in the study indicates that earth-based construction materials can generate significantly lower carbon emissions than conventional alternatives, with some estimates suggesting reductions of up to 80% when compared with common industrial materials (Parlato et al., 2023). Additional benefits include recyclability, improved indoor thermal stability, and the possibility of sourcing materials locally, all of which align with principles of circular economy and sustainable development (Melià et al., 2014; Lalicata et al., 2023). These characteristics position raw earth construction as a compelling alternative within a sector seeking carbon reduction and resource efficiency.

Although raw earth techniques have strong environmental credentials, their widespread adoption remains limited by concerns about durability, material variability, and inadequate practitioner knowledge (Losini et al., 2021; Santos et al., 2022). To address these issues, recent research has explored material stabilisation and enhancement strategies capable of improving strength, moisture resistance, and constructability (Guihéneuf et al., 2021; Cristelo et al., 2012). Such developments suggest that raw earth materials can be adapted for contemporary construction contexts, but they also reinforce the need for targeted training so that such innovations are understood and correctly applied in practice.

2.2 3D Printing in Construction

3D printing, or additive manufacturing, has become an increasingly important area of innovation in construction due to its potential to improve precision, reduce waste, shorten project timelines, and enable greater design flexibility (Varma et al., 2022; Puzatova et al., 2022). Extrusion-based systems are especially prominent in the field, allowing material to be deposited layer by layer according to digital models. These systems can work with a variety of material types and support greater control over material use than many conventional methods. For sustainable construction, this capacity is particularly relevant because it can reduce waste while also supporting the use of alternative, low-carbon material mixes.

A key precedent discussed in the study is the TECLA project by WASP and Mario Cucinella Architects, which demonstrates the integration of digital fabrication and raw earth construction at building scale. In the source study, Figure 4 presents a detailed axonometric section of the TECLA prototype, while Figure 5 shows the completed 3D-printed earth house. These examples illustrate how local raw earth materials and advanced printing technologies can be successfully combined to create low-impact housing solutions (Abdalla et al., 2021; Rossi, 2024). The TECLA case is significant not only as a technical achievement but also as a proof of concept for combining sustainable materials with digitally enabled construction practice.

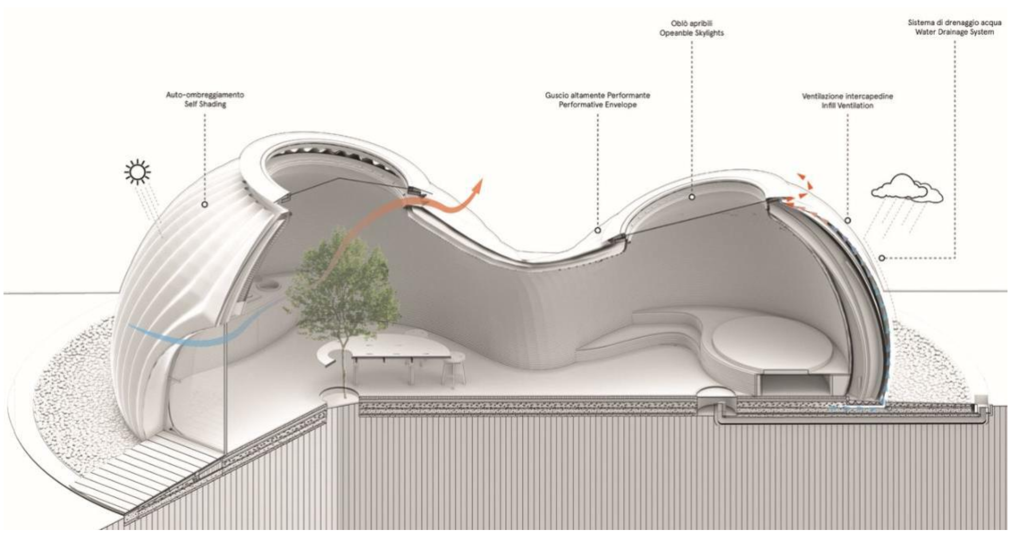

Figure 4: Detailed axonometric section of the TECLA prototype (Source: Pintos, 2021)

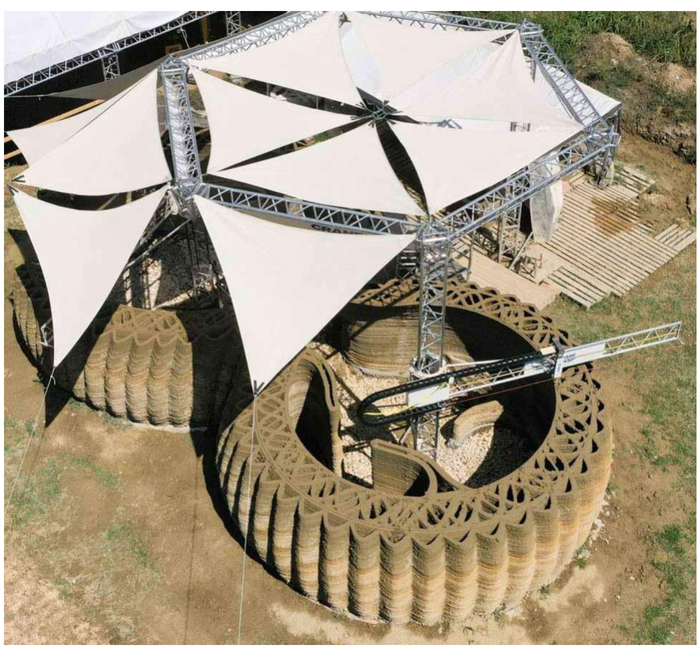

Figure 5: TECLA 3D-Printed House (Source: WASP)

Despite the promise of large-scale 3D printing, several challenges continue to limit its broader construction uptake. These include difficulties associated with material consistency, moisture control, scalability, printer logistics, and the absence of robust standards or regulatory frameworks (Estévez & Abdallah, 2022; El-Sayegh et al., 2020). In the context of earth-based materials, factors such as particle distribution, rheology, and layer bonding are especially important. As the study argues, these are not merely technical problems; they are also training problems. Construction professionals must understand both the behaviour of the material and the operation of the printing system if such methods are to be adopted effectively.

2.3 Virtual Reality in Construction Training

Virtual reality has become an increasingly significant tool in professional education because it offers immersive, interactive, and repeatable learning experiences. VR environments allow users to engage with simulated settings, objects, and procedures through head-mounted displays and controllers, giving them the opportunity to practise technical tasks without exposure to real-world risk (Siang et al., 2022; Mehrfard, 2020). In construction, VR has been applied to safety training, equipment familiarisation, hazard identification, and project visualisation, with research showing gains in learner engagement, situational awareness, and procedural understanding (Wang et al., 2018; Alizadehsalehi et al., 2021).

The educational advantages of VR are particularly relevant to emerging and complex construction processes. Because learners can rehearse tasks multiple times in controlled settings, VR supports experiential learning, feedback-based improvement, and confidence development (Stone et al., 2018; Michalski et al., 2019). The report highlights this point by drawing on studies that demonstrate improved training outcomes across fields such as healthcare, aviation, and technical maintenance, where procedural competence is critical (Checa et al., 2022; Korzeniowski et al., 2021). In construction contexts, these features make VR especially suitable for learning scenarios involving specialised technologies, advanced machinery, or sustainability-oriented workflows that are not yet widely available in everyday industry practice.

2.4 Integration Opportunities and Research Gaps

Although the literature on VR, 3D printing, and raw earth construction has grown considerably, the study identifies a substantial gap in their integrated application. Specifically, there is limited empirical research on how VR can support training for earth-based 3D printing, how immersive learning can bridge the divide between theory and practice in sustainable construction, and how effective pedagogical frameworks can be developed for this purpose (Tan et al., 2022; Wang et al., 2018). The results show that most of the reviewed literature has emerged in the last five years. Together, these gaps establish the rationale for the development and evaluation of EcoPrint VR.

3. Methodology

3.1 Research Design

The study adopted a convergent parallel mixed-methods design to evaluate the effectiveness of EcoPrint VR. Quantitative and qualitative data were collected during the same research phase so that measurable learning outcomes could be interpreted alongside participant perceptions and observed experiences (Creswell, 2018). The evaluation framework was adapted from Kirkpatrick's Four-Level Training Evaluation Model, with primary attention given to Level 1 (Reaction) and Level 2 (Learning) due to the time-bounded nature of the study. The conceptual basis for this evaluation framework is shown in Figure 6, which presents the hierarchical structure of training assessment from basic reaction to organisational results (Donald & James, 2006).

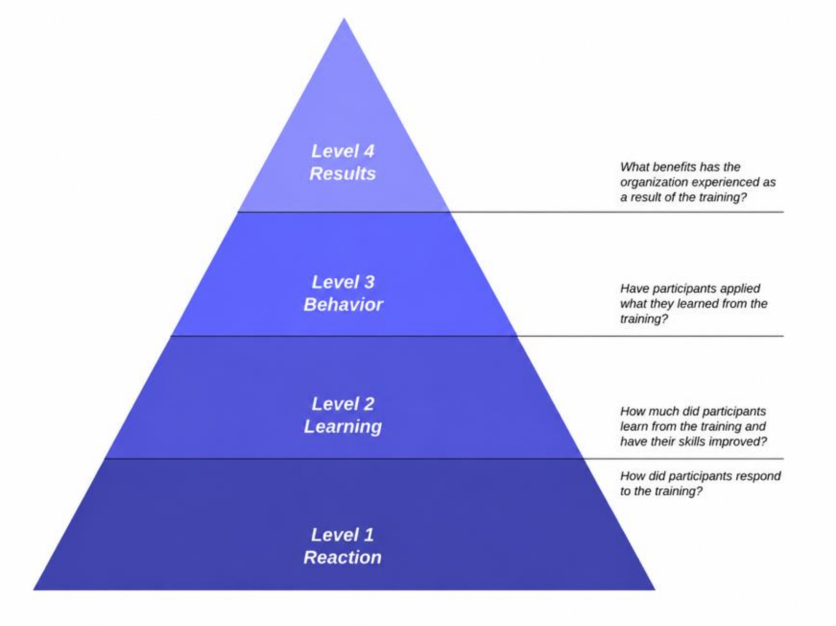

Figure 6: Kirkpatrick's Four-Level Training Evaluation Model (Source: Joshi, 2022)

3.2 Development of EcoPrint VR

The development of EcoPrint VR followed a structured sequence of five phases: investigation of current practices and requirements, storyboard development, technical implementation, experimental testing, and analysis. The system was built using Unity and designed to simulate realistic construction processes associated with 3D printing using earth-based materials. Instructional design was supported through a storyboard sequence, and the digital representation of the WASP 3D printer within the VR environment is shown in Figure 7. The training modules were intended to combine technical information with practical interaction in ways that reinforced both understanding and confidence.

Figure 7: WASP 3D Printer Setup in Virtual Reality Environment

3.3 Participants and Data Collection

The participant group comprised 10 PhD students from Massey University with varying backgrounds in education, age, experience, and industry role. While the sample was limited in size, it provided a range of perspectives that were useful in evaluating both the usability of the VR environment and its learning value. Data collection involved three main methods: pre-test and post-test questionnaires, informal qualitative discussions, and observation of user interaction during VR sessions. The pre-test measured demographics, prior experience, baseline knowledge, and confidence, while the post-test assessed knowledge gain, confidence changes, views on sustainability, and user experience. This combination of structured and open-ended data allowed for triangulation of findings.

3.4 Data Analysis

Quantitative data were analysed using descriptive statistics, paired t-tests, and Cohen's d effect sizes to determine changes between pre-test and post-test scores and to assess the practical magnitude of those changes (Field, 2018; Daniel, 2013). Qualitative responses were analysed thematically to identify recurring perceptions, concerns, and suggestions, while a word cloud was used to visualise the most frequently mentioned terms in participant feedback (Braun & Clarke, 2006; McNaught & Lam, 2010). By integrating quantitative and qualitative findings, the study aimed to generate a multi-dimensional understanding of how VR training influenced learning, confidence, and user perception.

4. Results

4.1 Participant Reaction (Level 1 Analysis)

Overall, participant responses indicated a positive reaction to the VR training experience. Users described the environment as immersive, interactive, and helpful in understanding complex procedures associated with earth-based 3D printing. Participants particularly valued the ability to engage with simulated construction processes in a setting where mistakes had no physical consequences and did not involve material cost or safety risk. These findings are consistent with prior VR training literature, which emphasises the value of immersive simulation in supporting engagement and conceptual understanding (Stone et al., 2018; Wang et al., 2018).

The qualitative feedback was further explored through word frequency analysis, visualised in Figure 8, where prominent terms included “confidence,” “understanding,” “engagement,” “machine operation,” and “material preparation.” These recurring themes suggest that participants experienced the training as both practically useful and cognitively engaging. User feedback also indicated broad satisfaction, with most participants reporting that the VR experience improved their awareness of sustainable construction processes and enhanced their confidence in interacting with unfamiliar technology.

Figure 8: Word Cloud of Participant Feedback on VR Training

At the same time, several participants reported usability issues. These included mild motion sickness, dizziness, and discomfort during longer periods of headset use, particularly among users wearing prescription glasses. Others expressed the need for more structured guidance, clearer step-by-step instructions, and additional interactive support features. These findings align with wider literature on VR usability, which notes the importance of ergonomic design and instructional clarity in immersive learning systems (Dimitrios et al., 2020; Li et al., 2018). The presence of both positive reactions and identifiable usability concerns suggests that while the training concept is strong, refinement is needed to optimise user experience.

4.2 Learning Outcomes (Level 2 Analysis)

The study evaluated learning across three measures: knowledge of 3D printing technology, confidence in operating a 3D printer, and confidence in material mixing and preparation. The statistical results are summarised in Table 1, which presents paired t-test outputs, p-values, and Cohen’s d effect sizes. The strongest gains were found in practical confidence measures. Confidence in operating a 3D printer increased significantly, with a large effect size ($d = 1.06$) and a statistically significant result ($p = 0.007$). Confidence in material preparation also increased significantly, with a large effect size ($d = 1.16$) and a p-value of 0.027. These correspond to improvements of 85% and 76%, respectively, indicating that the VR training was highly effective in supporting procedural confidence.

Table 1: Paired T-Test Results for Pre-Test and Post-Test Scores

Measure	T-Statistic	P-Value	Effect Size (Cohen's d)	Interpretation
Knowledge of 3D Printing	-1.54	0.159	0.71 (moderate effect)	Not statistically significant
Confidence in Using a 3D Printer	-3.50	0.007	1.06 (large effect)	Statistically significant ($p < 0.05$)
Confidence in Material Mixing	-2.65	0.027	1.16 (large effect)	Statistically significant ($p < 0.05$)

Knowledge of 3D printing technology also improved, but the change was more modest. While the effect size was moderate (d = 0.71), the difference between pre-test and post-test scores was not statistically significant (p = 0.159). This suggests that the VR platform was more effective in cultivating confidence and practical familiarity than in substantially deepening theoretical knowledge. The result is consistent with research indicating that immersive simulation often produces stronger gains in procedural and experiential learning than in abstract conceptual learning unless combined with additional instructional reinforcement (Makransky et al., 2019; Li et al., 2018).

4.3 Visual Analysis of Learning Gains

The visualisations reinforce the statistical findings. Figure 9 shows the Cohen's d effect sizes, making clear that practical confidence gains were substantially larger than knowledge gains. Figure 10 compares pre-test and post-test knowledge scores and shows moderate improvement with overlapping interquartile ranges. The results show clear upward shifts in medians and tighter post-test distributions, suggesting more consistent confidence among participants after the VR training. The visual evidence therefore supports the conclusion that EcoPrint VR was particularly effective in improving users' confidence in applying practical sustainable construction tasks.

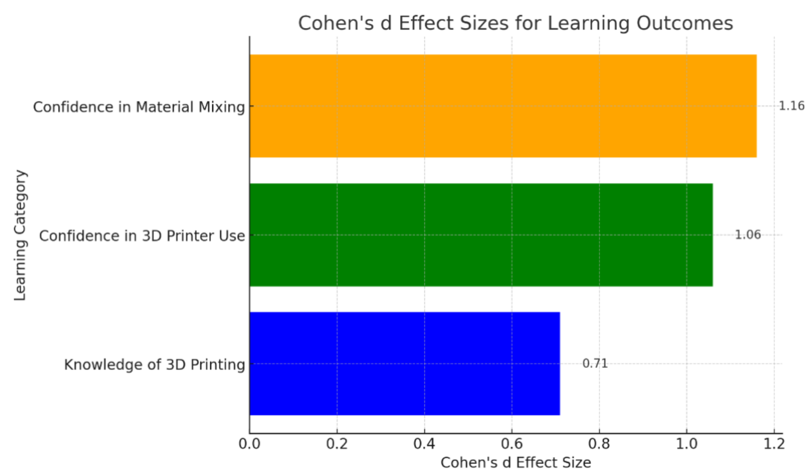

Figure 9: Word Cloud of Participant Feedback on VR Training

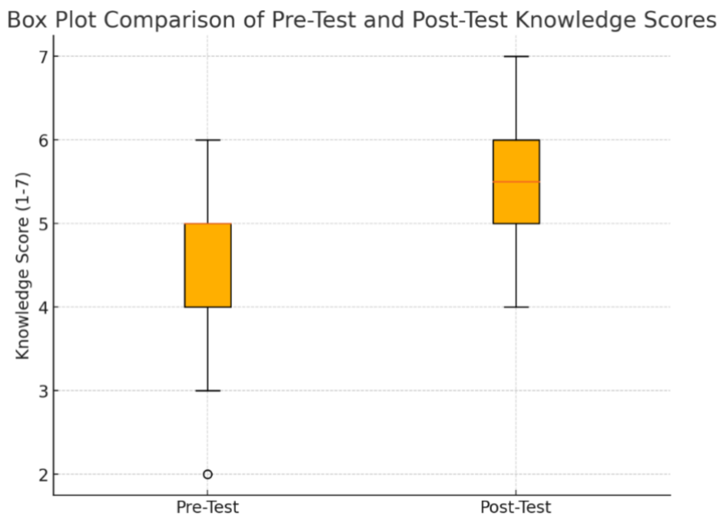

Figure 10: Box Plot Comparison of Pre-Test and Post-Test Knowledge Scores

5. Discussion

The findings indicate that VR can make an important contribution to sustainable construction training by helping learners move beyond theoretical awareness and into practical confidence-building. This is especially significant in the context of earth-based 3D printing, where access to machinery, materials, and demonstration opportunities may be limited. By simulating those conditions in a safe, low-risk environment, EcoPrint VR enabled participants to practise operational procedures and material preparation without physical waste, equipment costs, or safety concerns. This supports previous research showing that immersive learning environments are particularly effective for complex, skill-based tasks that benefit from repetition, interaction, and embodied practice (Vergara et al., 2017; Wang et al., 2018).

The broader significance of these results extends beyond immediate learner outcomes. The study suggests that VR-based training has the potential to reduce training costs by 40%, decrease material waste, and contribute to lower-carbon training practices by substituting some aspects of physical training with digital simulation. In a sector where sustainability and productivity are often treated as competing priorities, this is an important finding. It implies that immersive digital learning systems can support both workforce development and environmental responsibility simultaneously. The use of VR in this way therefore aligns not only with educational innovation but also with broader industry transitions toward resource efficiency and low-carbon practice (Li, 2023; Liu, 2024).

However, the study also demonstrates that VR training should not be viewed as a complete substitute for all other forms of instruction. The comparatively moderate improvement in theoretical knowledge suggests that immersive simulation alone may be insufficient for developing deep conceptual understanding. More structured pedagogical elements, including tutorials, quizzes, explanatory prompts, and scenario-based guidance, are likely needed to reinforce abstract and technical content. Participant calls for better guidance and comfort settings also indicate that human-centred design is essential if such systems are to be adopted widely and used effectively. Thus, the future role of VR in sustainable construction training will depend not just on the realism of the simulation, but on the strength of the educational design underpinning it.

6. Conclusion

This article has examined whether virtual reality can help build a more sustainable construction industry by supporting training for 3D printing with raw earth materials. The findings from the EcoPrint VR study suggest that immersive training can significantly improve confidence in practical construction tasks, particularly in operating 3D printers and preparing earth-based material mixes. Participants also perceived the VR environment as engaging, realistic, and valuable for learning, especially because it allowed them to experiment with processes in a safe and interactive way. These outcomes indicate that VR has considerable potential to support the adoption of sustainable construction technologies by strengthening practical readiness and reducing barriers to access.

At the same time, the study identifies important limitations and opportunities for future development. Improvements are needed in relation to user comfort, instructional scaffolding, and the reinforcement of theoretical knowledge. Future research should also extend beyond immediate learning outcomes to examine whether gains in confidence and understanding translate into on-site behaviour and organisational impact over time. Nevertheless, the evidence presented here suggests that VR can serve as a meaningful enabler of sustainable construction transition, not only by supporting skill development but also by helping reduce training waste, improve learning accessibility, and prepare the workforce for emerging low-carbon and digitally enabled modes of practice.

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