

The impact of technology on minoritized students' agency and environmental responsibility

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Abstract: The purpose of this WIP research paper is to examine the role technology plays in the development of minoritized students' agency and environmental responsibility in sustainability-oriented informal engineering learning. The continuous advancements in low-cost and accessible technology have created new opportunities for technology-aided education. One such opportunity is the ability to support students in more closely interacting with global issues that may have been too expensive or logistically unrealistic earlier. Such new technologies, including Augmented Reality (AR), Virtual Reality (VR), Minecraft Education Edition video games, and Tinkercad (browser-based application for computer-aided design (CAD)), have the potential to help students better understand concepts pertaining to sustainability and the impact of engineering on the environment. In our work, we have learned that students' perceptions of environmental responsibility grow when they can conceptualize and recognize their agency and presence within environmental phenomena and related expectations from human actions. Students' knowledge of the relevance of sustainability in cities and farms and its impact on the environment advanced. Over the last four years, we have worked with over 40 students in a highly subsidized afterschool program that serves students in a gateway town in the Northeast with a largely minoritized population. We engaged these upper elementary and middle school students in various activities, including sustainable city and farm design. Our data collection has included a series of interviews before, during, and after workshops where they shared their understanding and decision-making relevant to sustainability, as well as observations during program activities. The research question for our study is: How does immersive technology impact minoritized students' agency and environmental responsibility? In this paper, we share how, as students develop a more concrete conceptualization of sustainability, their personal conceptions of sustainability shift. For some students, engaging with the technologies, as mentioned earlier, deepened their understanding of different elements of sustainability and their personal responsibility within sustainability. Additionally, engaging with these technologies allowed students to imagine alternate sustainable futures for their town. Using technology to educate youth on sustainability works towards the overarching goal of encouraging students to think more critically about the impact humans have on the environment and how individuals can contribute towards positive, sustainable change locally and develop long-term sustainability-oriented mental models.

Keywords: sustainability education, student agency, k-12 minoritized students, informal learning environment, immersive technologies

Introduction

As global environmental issues become increasingly pressing, education plays a critical role in fostering a generation that understands and values sustainability. Sustainability education has emerged as a vital component of global initiatives aimed at addressing the escalating environmental crisis [1]. Across the globe, there is a rising recognition of the need to integrate sustainability education into school curricula. Countries like Finland and Sweden have taken proactive steps by embedding sustainability education into their national education frameworks. For example, Finland reported that by 2023, 85% of its schools had adopted sustainability-focused curricula [2]. In contrast, the U.S. is seeing growing interest in sustainability education within K-12 schools, driven by support from administrators, educators, and legislators [3], [4]. State and federal education leaders are advocating for the rapid expansion of sustainability initiatives in schools [5]. However, despite this momentum, the field remains in its early stages, challenged by limited resources and guidance [6], [7].

Reports from the United Nations Educational, Scientific and Cultural Organization [8] emphasize that sustainability education plays a fundamental role in achieving the Sustainable Development Goals (SDGs), particularly Goal 4, which focuses on ensuring inclusive and equitable quality education [9]. Despite these global advancements, many underserved and minoritized communities continue to face barriers to accessing sustainability education. Systemic inequalities, such as limited resources, lack of trained educators, and underrepresentation in STEM fields, pose challenges for equitable learning opportunities [10]. These differences highlight the need for innovative strategies to bridge the gap and make sustainability education accessible to all students, particularly those from marginalized backgrounds.

A promising approach to integrating sustainability education into K-12 engineering education is through the use of technology that provides opportunities for the development of collaboration and systems thinking, offering new pathways to enhance engagement and learning outcomes [11]. Immersive technologies such as augmented reality (AR), and virtual reality (VR), Minecraft Education Edition video games, and Tinkercad (browser-based application for computer-aided design (CAD)) have gained prominence for their ability to transform complex and abstract sustainability concepts into tangible and interactive experiences [12]. These tools facilitate experiential engineering learning, enabling students to visualize and engage with environmental phenomena in ways that were previously unattainable. By making abstract ideas more concrete, immersive technologies provide learners with opportunities to explore sustainability challenges and solutions in realistic, virtual contexts. Furthermore, the increasing accessibility and affordability of these immersive technologies have democratized their use in educational settings, broadening opportunities for diverse and underrepresented student populations to actively participate in sustainability-focused learning. As technology continues to evolve, it presents a unique opportunity to address educational disparities and support the development of sustainability-oriented mindsets among minoritized students. By using these tools, educators can create more inclusive and engaging learning environments that not only support environmental responsibility but also empower students to visualize and build sustainable futures [13], [14].

Literature review

Technology in Sustainability Education

Ozturk and Akcay, investigated the impact of AR applications on the environmental knowledge, attitudes, and behaviors of primary school third-grade students. Conducted with 17 students using a case study design, the research involved six weeks of AR-supported environmental education sessions, where students explored environmental concepts through immersive digital tools. The findings revealed that AR applications significantly enhanced students' environmental knowledge, fostered positive attitudes, and

encouraged environmentally friendly behaviors, such as recycling and caring for living organisms. Additionally, students expressed enjoyment and increased engagement, suggesting AR's potential to make environmental education more effective and appealing [15].

In another study, Ma et al., conducted research on the use of AR gamification in sustainability education to enhance environmental awareness and promote low-carbon living habits among students in Hong Kong. Using a mobile application incorporating simulation games, animations, and interactive elements, the research aimed to teach practical ecological concepts while motivating learners through achievement-based rewards. The study employed pre- and post-surveys with 130 students to measure changes in knowledge and attitudes. Results indicated significant improvements in students' understanding of renewable energy, waste reduction, and sustainable living practices, alongside increased interest and motivation in environmental learning [16].

An investigation examined the use of mobile VR for environmental education among 64 secondary school students in the UK. During a geography field trip, students used the Google Expeditions VR app to explore 360-degree virtual environments, comparing their local nature reserve to the Borneo rainforest. The immersive VR experience enhanced students' understanding of large-scale environmental changes caused by deforestation and urban development. Post-field trip reflections and letters to a conservation society demonstrated improved environmental awareness, critical thinking, and motivation to take action for ecological preservation. The study highlights VR's potential to enrich experiential learning in environmental education [17].

A recent study evaluated the effectiveness of VR in environmental education by comparing 100 middle school students split into VR-based and traditional learning groups. Using pre- and post-tests and feedback, the research assessed knowledge retention, engagement, and attitudes. Results showed that VR significantly improved understanding, engagement, and pro-environmental attitudes by immersing students in virtual ecosystems and environmental scenarios, making complex concepts more accessible and impactful. This highlights VR's potential as an innovative tool for enhancing environmental education [18].

According to McNally and Andrade, Minecraft has the potential to impact the way people learn about and interact with the natural world [19]. Building a house for one's own use and aesthetic appeal is a common first project for amateur builders, according to Harrison and Gesthuizen [20]. In addition, children can gain a lot of understanding about sustainable living ideas, challenges, and opportunities by touring a virtual city [21].

Studies involving pre-service teachers found that CAD aids learning retention. Doğan and Kahraman suggest that Tinkercad's spatial interface can enhance students' interests, attitudes, and motivations [22]. Mohapatra et al. stated that Tinkercad is affordable, user-friendly, and easy to use [23]. Researchers and practitioners have engaged learners in several contexts with Tinkercad. Cherry, taught Tinkercad 3D character animation for short films [24]. Students used 3D Food printers to produce Tinkercad dessert designs by Kuo, Laiy, and Kao [25]. In a study conducted by Ng, math teachers used 3D CAD and printing to help pupils grasp solid volume [26]. Additionally, Madar et al. created C3d.io, which lets students experience their Tinkercad designs as prototypes in VR and share the latest version online [27].

In addition, Tinkercad is a valuable tool in teaching and learning, especially in STEM education, as it allows students to engage in hands-on, creative design and digital creation. It serves as an accessible entry point to 3D modeling and engineering, developing creativity while reinforcing critical thinking and problem-solving skills [28]. The platform's user-friendly interface encourages active learning and collaboration, as students can work together on projects and share their designs for feedback [29].

Moreover, Tinkercad's integration with 3D printing brings students' digital creations to life, bridging the gap between the virtual and physical worlds and improving their understanding of design principles [28].

Agency and Environmental Responsibility

A study by Vossoughi and Shea explored the concept of a Critical Science Agency (CSA) and its role in fostering justice-oriented science education. CSA involves youth developing expertise in both science and their community, using this knowledge to address community issues collectively and ensuring these actions are justice-driven. The authors highlighted examples, such as students designing a sustainable hand-crank energy source instead of using batteries, to demonstrate CSA in practice. This example illustrated how integrating "science knowledge" with "community knowledge" can foster meaningful learning and social impact. The paper also discussed the complexity of agency, noting that actions might seem agentic but could simply follow instructions, while smaller acts could reflect resistance or creativity. Advocating for participatory methodologies, the authors emphasized the importance of understanding the interplay between educational designs, student autonomy, and broader social structures to support transformative learning experiences [30].

Cavagnetto et al. explored how to foster agency in science education through "authorship," where students actively participated in generating knowledge. The study highlighted that agency depended on balancing the benefits (e.g., engagement, learning) with the costs (e.g., effort, social critique) of participation. They emphasized creating safe environments with constructive critique and allowing students to engage deeply in tasks like designing experiments and analyzing data. Using examples like the Science Writing Heuristic approach, the study showed how inquiry-based practices improved critical thinking, retention, and confidence in science [31].

Methodology

In this study, we employed a case study methodology to explore the development of agency among multiple students in an informal engineering education context. Case study research is well-suited for examining complex phenomena within real-life contexts, allowing for an in-depth analysis of students' experiences and interactions [32]. This method enabled us to investigate how individual factors, such as personal interests and motivations, and collective factors, such as peer collaboration, group decision-making, and shared problem-solving during sustainability-focused activities, influenced student agency within the learning environment. We use this methodology to answer the research question: ***how do immersive technologies influence the development of minoritized students' agency and environmental responsibility within sustainability-focused informal engineering education?***

Research Context

Over the past three years, starting in September 2021, our program has undergone five iterations, each introducing or enhancing activities to explore how educational immersive technology can support mental models focused on sustainability in informal engineering education. These improvements aimed to boost student engagement and understanding of sustainability in an engineering context. The workshop employed immersive technologies such as AR, VR, Minecraft, and Tinkercad to investigate their influence on enhancing agency and environmental responsibility among minoritized students within the context of sustainability-oriented informal engineering education.

Participants

During the five iterations of our workshop, over 40 students participated in the study, with an average of about 12 middle and upper elementary school students in each iteration. This analysis focuses on five students who participated consistently, forming the basis of this study. The five participants (see Table 1) comprised three females and two males, ranging from grades 6 to 8 and ages 11 to 14.

Table 1. Demographic information of participants.

Name	Gender	Age	Grade
Brenda	Female	13-14	8
Laticia	Female	13-14	8
Sandra	Female	13-14	8
Jarod	Male	13-14	8
David	Male	11-12	6

These students provided rich data through pre- and post-interviews, observations, and project artifacts. Data collection in informal, afterschool programs is often challenging due to the voluntary nature of participation. Students joined voluntarily and provided informed consent via child assent and parental permission forms. Each participant received a \$25 gift card as a token of appreciation. To ensure privacy, pseudonyms were used, and students were not required to prioritize the workshop over other commitments.

Data Collection Tools

To explore the research questions, we collected qualitative data through various methods, including interviews conducted before and after the workshops, video and audio recordings capturing participants' discussions during activities, and detailed observations of their engagement. Each interview lasted between 5 and 10 minutes, allowing students to express their evolving understanding of sustainability and reflect on their experiences with the workshop activities.

Data Analysis

We utilized qualitative narrative and artifact analysis to address our research questions. A grounded approach was applied to structure the data, followed by the creation of a codebook refined through collaborative discussions to maintain consistency [33]. Three researchers independently performed open and thematic analysis to identify recurring patterns and organize the data into codes [34]. This approach provided valuable insights into how immersive technologies influenced minoritized students' agency and sense of environmental responsibility through their engagement in digital city and farm design processes. The codes were later reorganized into themes through collective discussions, ensuring consistency, reducing bias, and enhancing the reliability of the study [35].

Research Settings

Our workshop took place in an after-school program located in an urban gateway town in the northeastern United States. The program offered a supportive, low-pressure environment where students could explore

a variety of informal engineering design activities using technology. The workshop design incorporated a range of immersive technologies, including AR, VR, Minecraft, and TinkerCad. At the start, the workshops introduced students to sustainability and AR technology, encouraging them to design a digital sustainable city using the CoSpaces Edu platform. For AR, students utilized CoSpaces Edu (an online platform that enables students to create 3D models and animate them using code) and MERGE Cube (a physical cube that serves as an AR canvas) as web-based mixed-reality tools to create and interact with virtual environments collaboratively. They combined visual coding with tangible objects and worked in teams to balance design requirements with available resources. Students coded their city designs, explained their choices, and presented their projects using MERGE Cube and iPads. This hands-on approach enabled students to understand engineering trade-offs and programming concepts effectively.

In the next phase, students used VR headsets and the Wander app. The Wander app allowed students to travel the world virtually. For the activity, they explored cities, identified sustainable and unsustainable features, and were tasked with discussing and proposing sustainable solutions for these places to foster their critical thinking and problem-solving skills. Another activity had students locate areas in their town of Framingham, observe the design, and suggest improvements. They also worked in pairs to find specific items from a checklist. After each activity, students discussed their findings in groups to deepen their understanding of sustainability concepts.

Following this, students interacted with Minecraft Education Edition, a version tailored for educational settings that enables teachers to regulate gameplay by minimizing violence and character damage [36]. The selected worlds emphasized sustainability themes, such as Sustainable Cities and Sustainable Farming (Minecraft, n.d.). Sustainable City features six lessons that explore how students' environmental choices impact the world. Through these lessons, students studied topics like water treatment, sustainable food production, and green building design. Sustainable Farming, on the other hand, highlights agricultural practices and principles of sustainability.

The final technology used in the workshop was TinkerCad, a three-dimensional CAD software for creating models with precise dimensions in virtual environments. Students were introduced to TinkerCad and its essential tools, including navigating the workspace, drawing shapes, and adjusting objects. For practice, they designed personalized name tags. Students modeled a sustainable farm featuring elements such as solar panels, rainwater systems, and crop fields. They then progressed to designing sustainable cities, incorporating green buildings, public transit, renewable energy, and waste management systems. Working in teams, students prioritized key components such as renewable energy sources, public transit, and green spaces based on sustainability criteria. They reflected on their decisions and discussed trade-offs involved in urban planning. These activities developed a deeper understanding of sustainability, which was assessed through post-interviews.

Findings

This section presents the cases of five students, examining how their pre- and post-interviews before and after attending different workshops reflected their changing ideas about sustainability. Each case story illustrates how hands-on technology-enhanced experiences and group engineering design and problem-solving impacted students' perceptions about sustainability, which were frequently vague or based on individual experiences. The workshop activities were designed to encourage problem-solving and collective engineering design, which was important in increasing students' agency. Throughout the workshops, students worked together to develop sustainable cities and farms with tools like Tinkercad, Minecraft, and AR/VR applications. These activities encouraged them to negotiate design decisions, assign roles, and resolve problems collaboratively, simulating real-world engineering teams. Students revised their designs based on feedback via iterative prototyping and group discussions, which improved their ability to make independent decisions and take control of their learning experience. This

collaborative approach not only increased their technical skills and systems thinking but also empowered them to see themselves as active contributors to sustainable solutions, supporting their feeling of agency in environmental responsibility and engineering design. These results show how the workshops affected students' ability to relate sustainability-related ideas to practical uses, exhibit agency in their choices, and critically evaluate their educational experiences.

Brenda

In a 2022 pre-interview conducted before starting the workshop, Brenda was asked about her understanding of sustainability. When asked what sustainability meant, she said, *"I think like strength or something?"* When prompted about sustainable actions, she replied, *"helping the environment."* To a question about how her family could personally help the environment, she responded, *"donating. To like younger people."* Brenda's initial understanding of sustainability appeared to focus more on social-related actions such as donating to younger people. She acknowledged the connection between sustainability and the environment, but her response lacked specific references to environmental practices or concepts, suggesting that her understanding may have been broad or underdeveloped at this stage.

By the 2023 pre-interview, Brenda's perspective on sustainability suggested a developing understanding. She described it as *"like something that will help the world"* and provided examples such as *"like solar panels, trash cans, recycling."* She demonstrated a clearer understanding by identifying multiple concrete actions that can benefit the environment. When asked about sustainable ways of living, she suggested, *"start to use like window blinds or something. And, uh, Recycle more."* Brenda's growing awareness of sustainability was also evident when she proposed changes to her lifestyle, stating, *"probably, like, make bikes the speed of a car, so we use less gas. Like people just can ride a bike."* Here, Brenda's response suggests an emerging awareness of the environmental impact of gas usage and the potential for alternative transportation. In the 2023 post-interview, Brenda's understanding became more detailed. She defined sustainability as, *"It means like to sustain stuff, like, save stuff, and don't use it to like ruin the world."* This definition suggests a developing understanding as she, emphasized resource preservation and preventing environmental harm. When asked to name sustainable actions, she mentioned, *"using, like, these blind things that we have around. And um using like, less cars, so you pollute everywhere. And stop with a lot of factories."* These examples indicate an increasing awareness of environmental impact, particularly related to pollution and industrial activity. When asked what she would change to make life more sustainable, she simply stated, *"more grass,"* highlighting her developing yet personal view of sustainability, though she did not elaborate on its broader environmental significance.

In the 2024 post-interview, Brenda explained her decision to incorporate bikes into her city design as a way to reduce gas emissions. When asked why she chose bikes over other forms of transportation, she said, *"cause that's the only thing I know how to drive!"* While her reasoning was personal, it reinforced her earlier recognition of bikes as a sustainable mode of transportation. This choice showed Brenda's sense of agency in committing to practical and accessible ways to contribute to sustainability. Her consistent focus on bikes suggests that her approach to sustainable living was shaped by personal familiarity and accessibility, indicating a growing but still-developing understanding of sustainability. Brenda's journey demonstrates a developing awareness and growing sense of agency as she connected sustainability concepts to her actions that felt practical and personally relevant. However, her reasoning remained closely tied to her personal experiences rather than a fully articulated sustainability framework.

Sandra

In a 2022 pre-interview, Sandra was asked what sustainability means. She responded, *"I don't know. Um to build I think?"* When prompted for examples of sustainability, she said, *"like make good choices and like do the right thing."* When asked if her family takes any sustainable actions, she replied, *"we do the right thing."* To provide an example of something sustainable in her house, she explained, *"It's just like*

how um like we don't have to worry because like we lock all our doors if we're not outside and we don't leave the doors like unlocked unless we have a key and are just playing in the backyard." Sandra emphasized the importance of sustainability by stating, *"you don't want to end up living in like a place where it's not going to be safe for you."* Her definition of sustainability *"to build, I think"* reflects uncertainty, while her examples, such as *"make good choices"* and *"do the right thing,"* show a broad moral perspective rather than a focused understanding of sustainable practices. Her response suggests that she associated sustainability with personal and household security, evidenced by locking doors and ensuring safety, rather than environmental or resource-related practices.

By the 2023 post-interview, Sandra showed a clearer understanding of sustainability. She shared that she learned *"that solar panels and trees and pavement are all sustainable."* When asked what new information she learned, she explained, *"that actually cars are not sustainable because they carry the least amount of people."* This response highlights her recognition that cars are less sustainable but did not explicitly explain why. When asked if she would like to live more sustainably, Sandra responded, *"I would but like I don't really know what I would change."* However, she described practical actions she already takes, such as, *"I'd like keep my window open. Because it like instead of using like AC it like brings like cold air and also I opened like my shades to like bring in the sun and where I close them to keep the sun out."* These responses indicate an awareness of energy-saving behaviors but do not explicitly frame them as sustainability actions.

Sandra's responses from 2022 to 2023 show a shift in her understanding of sustainability. Initially, she viewed sustainability as related to personal safety and general moral ideas as seen in her emphasis on *"doing the right thing"* and locking doors for safety. After the workshop, her understanding of sustainability became more informed and specific, as she identified specific sustainable elements, such as solar panels and trees, and acknowledged that cars are *"not sustainable because they carry the least amount of people."* While she expressed uncertainty about how to live more sustainably, she described actions related to energy use, reflecting a growing awareness of personal habits that align with sustainability.

Jarod

In a 2022 pre-interview, Jarod was asked about his thoughts on engineering design and sustainability. When asked what sustainability means, he answered that the *"first thing that comes to mind is durability"* and went on to define durability as *"how much you can, like-- Yeah, withstand."* This demonstrates that Jarod initially associated sustainability with durability, defining it in terms of withstanding force. When prompted about sustainable actions his family might take, he replied, *"move around, like get energized?"* This indicates he connected sustainability with energy and movement, though he was still unclear about how this related to sustainability. When asked about a sustainable place, he stated, *"sustainable... well it's definitely not Ukraine...my head is telling me Ukraine is not sustainable because it's being attacked."* This response illustrates how Jarod linked sustainability with stability and safety, as he described Ukraine as 'not sustainable' because it was being attacked. Jarod's initial understanding of sustainability appeared to be centered on durability, movement, and safety, with no apparent connection to environmental aspects of sustainability.

In a 2023 post-interview conducted after the workshop, Jarod's understanding of sustainability had shifted. When asked to define it again, he stated, *"it means like, how like uh, environmentally like friendly,"* indicating a shift from associating sustainability with strength to connecting it with environmental friendliness. When asked if he would want to live more sustainably, he responded, *"yes, and um, I don't think this is really relevant to it, but I'd like to climb a tree,"* suggesting a personal connection between sustainability and nature. This marks a shift from his earlier focus on durability and energy toward an awareness of environment factors. Jarod also described his work during the workshop, where he added, *"solar panel, you know, just to keep--just to keep it sustainable"* to his apartment design.

He explained that solar panels “*they use like sunlight to generate the power and stuff instead of the other ways to generate power,*” demonstrating that he incorporated sustainability-related elements into his design. When asked about his experience with AR, he described it as “*very cool and interesting,*” noting that he found it exciting. These responses show that Jarod not only expanded his understanding of sustainability but also developed a sense of agency, and incorporated related concepts into his design.

Jarod’s journey highlights a transformation in his understanding of sustainability. Initially focused on concepts like durability and security, his experience in the workshop expanded his perspective to include environmental awareness and practical applications, reflecting his evolving perspective that included environmental considerations and sustainability design elements.

Laticia

In a 2022 pre-interview, Laticia was asked what sustainability means, and she responded, “*I’ve heard of it. But I don’t like... I didn’t get into it,*” adding that she thinks it means “*having stuff like, tie in like making sure like you know what it is and stuff.*” This suggests that while she recognized the concept of sustainability, she was uncertain about its definition, possibly associating it with “*having stuff like, tie in like making sure like you know what it is and stuff.*”. When asked for examples of living a sustainable life, she said, “*having good, like a good um shelter. And like, having like decent amount of money and stuff like that to like help you live,*” indicating that she associated sustainability with stability in life, particularly through secure housing and financial resources. She further explained, “*me and my family have like a good good shelter. Like it won’t like easily, like start breaking down,*” showing that she viewed sustainability as linked to having a durable and secure place to live. When asked if technology can be sustainable, she responded, “*yeah. Because like it’s like there’s um like a lot of like because a lot of people use it and it’s like popular and stuff,*” suggesting she associated sustainability with the common use and importance of technology in daily life.

In a 2023 post-interview, Laticia demonstrated a shift in her understanding of sustainability. When asked what new information she learned, she said, “*that it’s good for the environment. like that, like, it uses, like, transportation and like green. Like good, like, like grass, and like, bushes and stuff like that,*” suggesting that she associated sustainability with environmentally friendly elements such as transportation and greenery. She explained that “*bikes are sustainable, and like scooters and stuff,*” highlighting she recognized bikes and scooters as sustainable forms of transportation. Additionally, she noted, “*I walk home too, so like I don’t waste energy from my mom’s like gas from my mom’s car,*” showing how she connected the activity to her own actions, such as choosing to walk rather than using her mom’s car.

During the activity, Laticia identified a “*broken windmill*” as a sustainability issue, explaining that non-functioning machinery negatively impacts people. Her proposed solution was “*having people rebuild it. Or like adding other stuff that like connects to it and works the same way,*” demonstrating her understanding of sustainability as ensuring that technology remains functional and beneficial for people. She also described how, “*for some of the houses I put like windmills and like solar panels on top of the buildings,*” showing her knowledge of how sustainable technologies such as windmills and solar panels could be integrated into urban design.

Comparing Laticia’s pre- and post-interviews reveals a shift in her perception of sustainability, expanding beyond resources and stability to include environmental elements. Initially, she associated sustainability with having resources and sturdy materials for a comfortable life. After the workshop, her understanding expanded to include environmental preservation, sustainable transportation, and the use of renewable energy technologies. This progression highlights her ability to apply sustainability concepts in practical and creative ways, particularly in designing cities through the addition of windmills and solar panels.

David

In a 2024 pre-interview, David was asked questions about sustainability and living a sustainable life. When asked what sustainability meant, he admitted he was not sure how to define it, but when prompted for examples of sustainable living, he described, “*recycling, um saving- using less water, no littering, composting.*” These examples demonstrate that, despite his uncertainty about the definition, David was familiar with several environmentally friendly actions. When asked what he would change to create more sustainable lives, he explained, “*I would change how trash is..like make the trash disappear,*” showing that he saw waste as an issue and imagined a way to eliminate it. He envisioned a solution where trash could simply disappear, suggesting that he recognized trash as a problem but did not specify its broader environmental impact. This pre-interview illustrates David’s sense of agency, his interest in sustainability-related challenges and his willingness to consider solutions.

In a 2024 post-interview, David reflected on the new information he learned from the workshop. He stated, “*I learned a lot about like, how to take care of the environment,*” emphasizing that his biggest takeaway was about environmental responsibility. In his design of a sustainable city, he incorporated renewable energy sources, such as “*winter bands, solar panels and things that can help you.*” David also shared his experience using technologies like Minecraft and TinkerCAD, expressing a preference for Minecraft because; “*in Minecraft like you can do pause and fill in detail to the way you want to,*” allowing him to create complicated designs.

David’s pre- and post-interviews highlight the value of immersive technologies like Minecraft and TinkerCAD in supporting his learning. These tools provided a way for him to create and refine his designs while exploring sustainable design concepts. Comparing his responses before and after the workshop, his statements suggest a broadened understanding of sustainability and an increased interest in applying these ideas. This shift demonstrates that the workshop helped David to develop his initial ideas into more structured concepts related to sustainability.

Discussion

The incorporation of technology into sustainability education proves to be helpful for developing engaging and effective lessons. VR facilitated students in experiencing landscapes from around the world, which they subsequently applied to their urban design projects. Students enhanced their comprehension of new concepts by integrating experiences from their backgrounds through significant interactions with technology. The workshops enabled students to understand their agency in sustainable action by recognizing practical steps applicable to their daily lives. Environmental issues impact all individuals, underscoring the necessity of equitable environmental education to enable all learners to engage in sustainable solutions. The findings demonstrate that immersive technologies, including VR, AR, Minecraft, and TinkerCad, supported shifts in students' sustainability comprehension from abstract concepts to actionable and practical knowledge. Jarod initially linked sustainability to durability and resilience; however, he later adopted a more comprehensive perspective that included environmental friendliness and renewable energy solutions.

In the same way, Sandra's somewhat broad conception of “doing the right thing” developed into recognizing specific sustainable practices, such as the implementation of solar panels and the use of energy-efficient transportation. These examples illustrate the affordances of technology to link theoretical learning with practical applications, allowing students to relate sustainability concepts to their personal experiences and cultural contexts. These activities enabled students to enhance their critical socio-technical literacy, thereby increasing their independence and autonomy in addressing environmental challenges in their communities.

Prior research indicates that educational technologies provide immersive and engaging learning experiences for youth. Deterding et al. indicate that the immersive characteristics of VR enhance learner

engagement by fostering a sense of presence within virtual environments [37]. Chang and Chen demonstrated that AR lessons motivated and engaged students to a greater extent than conventional teaching methods [38]. Tudor et al. believed that Minecraft has the potential to be a "game-changer" for educating and connecting with nature [17]. Doğan and Kahraman suggest that Tinkercad's spatial interface can enhance students' interests, attitudes, and motivations [22]. Further, according to Beheshti et al., integrating technologies like AR, VR, educational video games, and CAD tools into K–12 sustainability-focused engineering education enhances student engagement, understanding, and skills. AR and VR provide immersive experiences that simplify complex sustainability concepts, while tools like Minecraft and Tinkercad foster creativity, collaboration, and problem-solving. These technologies bridge theoretical principles with real-world applications, empowering students to take actionable steps toward addressing environmental challenges [14].

The technology-enhanced engineering design workshops promoted systems thinking and agency among participants. Students David and Laticia showed their ability to envision and propose practical solutions through the design of sustainable cities, incorporating renewable energy sources, and addressing challenges such as waste management. Collaborative discussions enhanced these experiences, enabling students to refine their ideas through collective problem-solving. The integration of technology-enhanced creativity and engagement supported the development of critical skills necessary for analyzing the environmental impact of human actions.

The findings from this study, coupled with the outcomes of the workshops, underscore the need for equitable and accessible sustainability-oriented education in informal engineering education settings, especially for younger learners, to prepare future generations to address global environmental issues.

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