Enhancing Students Engagement in Environmental Engineering through Virtual Reality–Based Bioreactor Activities

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Abstract

Activities of a 30 L bioreactor in virtual reality (VR), initially developed for a bioprocessing laboratory course, were introduced to an environmental engineering laboratory course. The overarching purpose of these VR-based bioreactor activities is to expose students to basic bioreactor learning through immersive engagement, analyze students' responses, and explore the feasibility of creating a future lab module using VR technology. This study examines the role of VR technology in enhancing student engagement and learning within the lab course. To explore this objective, we asked the following two research questions: (1) How does VR technology enhance student engagement in bioreactor learning? (2) How do students describe and reflect on their learning experiences following engagement with VR technology in bioreactor learning?

The data analyzed in this study consists of 13 participants enrolled in the environmental engineering laboratory course. First, participants were given five minutes to explore as many components of a bioreactor as possible and describe the component inside the bioreactor using VR technology; this activity provided a baseline measure of engagement. Second, participants completed a self-reported retrospective survey in Qualtrics consisting of close-ended items and open-ended reflections on the VR experience. Survey responses were analyzed using thematic analysis to identify recurring patterns and insights into students' engagement and learning during the VR activity.

The post-activity assessment showed strong bioreactor component engagement among students who participated in the VR-based bioreactor activity. Of the 13 participants, 11 students (85%) identified 30 or more of the 35 bioreactor components presented. Qualitative feedback further reinforced this interpretation, with students reporting that the VR experience felt "like a field trip," "realistic perspective," "felt like I was actually there," and "3D interaction and immersion." Overall, the combination of high component recognition rates and vivid learner feedback demonstrates how VR technology bridges the gap between complex environmental engineering concepts and tangible, real-world applications. These results suggest that VR technology can encourage students' engagement in environmental engineering education.

Keywords: virtual reality, bioreactor, learning engagement, environmental engineering lab

1. Background

In engineering education, students are often confronted with complex real-world systems that can be difficult to comprehend without physical interaction with them. To bridge this gap, educators increasingly emphasize engagement as the foundation of meaningful learning. Engaged students demonstrate higher learning gains, improved retention of difficult concepts, and a stronger ability to apply knowledge to real-world systems [1-3]. This is especially critical in environmental engineering courses, where students are not only required to grasp interdisciplinary principles but also to integrate knowledge, competencies, and ethical responsibility into designing systems that address pressing environmental needs [4].

Student engagement has been defined in multiple ways across literature. Fredricks et al.[5], however, central to the discourse is the recognition that it is a multidimensional construct that can be conceptualized as comprising four dimensions: behavioral engagement, cognitive engagement, emotional (or affective) engagement, and, more recently, agentic engagement. The cognitive, behavioral, and emotional dimensions were first synthesized clearly in the foundational work of Fredricks et al [6]. Behavioral engagement refers to students' attendance, participation, effort, and task completion. Cognitive engagement encompasses the mental investment necessary for deep learning, including the strategic use of resources and self-regulation. Emotional engagement reflects students' interest, motivation, and enjoyment. Agentic engagement, a relatively recent addition to literature, describes students' proactive contributions to the learning process by expressing preferences, asking questions, and influencing instructional experiences [1, 7]. Collectively, these four dimensions provide a comprehensive framework for understanding how students interact with and respond to instructional environments, particularly in complex fields such as engineering education.

Faculty as designers of educational environments play a significant role in fostering student engagement [8]. Engineering educators have employed various methods to promote student engagement, including collaborative learning, problem-based learning, simulation tools, and immersive technologies such as virtual reality (VR) [9]. Studies in immersive and simulation-based learning demonstrate that VR offers a particularly promising route in learning engagement because it can provide interactive 3-D immersive experiences that reduce abstraction, increase spatial awareness, ability to manipulate complex systems, and develop more comprehensive mental models of dynamic processes [3, 7]. Additionally, in situations where physical systems and field trips are not available, due to factors such as expense, accessibility, time, and safety, VR provides an alternative for interacting with those complex systems.

In terms of levels of engagement within VR environments, researchers distinguish at least three intertwined layers: (1) surface engagement, which involves attending to the virtual environment, exploring it, noticing features and interacting with controls [10]; (2) deep engagement, which consists of actively making sense of the system being simulated, linking virtual manipulations to underlying engineering concepts, and asking "why/how" questions [2, 8]; and (3) transfer-engagement, which involves using what has been learned in the VR environment to solve new or unfamiliar problems and to apply learning beyond the simulation [11]. The immersive VR context can scaffold movement from surface to deep to transfer engagement by providing realistic scenarios, immediate feedback, and opportunities for repeated experimentation in a safe space [12, 13].

Biological processes that use microbes, cells, and enzymes to produce desired products (e.g., biofuels, food, beverage, biopharmaceuticals) or treatments (e.g., waste and wastewater treatments) are critical to the fields of environmental, biological, chemical, and sustainability engineering. The bioreactor or fermenter is a key piece of equipment used in these biological processes. However, it is complex, expensive, and challenging to implement in undergraduate lab classes. To address this gap, conducting bioreactor orientation and experiments in VR presents a promising approach for teaching biological processes and industrial sustainability with bioreactors. Therefore, a VR-based bioreactor lab module was introduced to *Environmental Sustainability for Industry Laboratory*, an undergraduate lab course where physical bioreactors were not feasible due to facility capacity limitation and high expense. Student work collected was analyzed to understand baseline student engagement with the VR bioreactor and to answer the following research questions (RQs):

RQ 1: How does VR technology enhance student engagement in bioreactor learning?

RQ 2: How do students describe and reflect on their learning experiences following engagement with VR technology in bioreactor learning?

2. Methods

2.1 Development of the VR bioreactor

The 30 L bioreactor VR environment was initially developed for a bioprocessing lab course at another institution (NC State University). The 3D model of a BIOSTAT 30 L bioreactor was constructed in Autodesk Maya based on photographs of the unit taken from multiple angles and technical drawing diagrams of the main bioreactor connections. The interactive elements were built using Unity and the Playmaker asset, a virtual programming environment that allows for interactivity with minimum backend programming. A bioreactor orientation game was created using this interactive 30 L bioreactor model. The VR design is conducted by translating the game over to VR and setting up a VR camera to properly scale the model to the HTC Vive headset. Detailed VR bioreactor development was documented in previous publications [1, 14].

In the final 30 L bioreactor VR environment (Figure 1), users can move freely around the bioreactor, step closer or crouch down to examine components, and even move inside the bioreactor to view internal components. VR hand controls are used to engage with the 3D space. Thirty-five key components of the bioreactor system, including main bioreactor components, utility pipes, and ancillary equipment, are labeled. As the user looks at each key component, it is highlighted, with a label displayed above it and a counter showing the progress of components viewed (Figure 2).

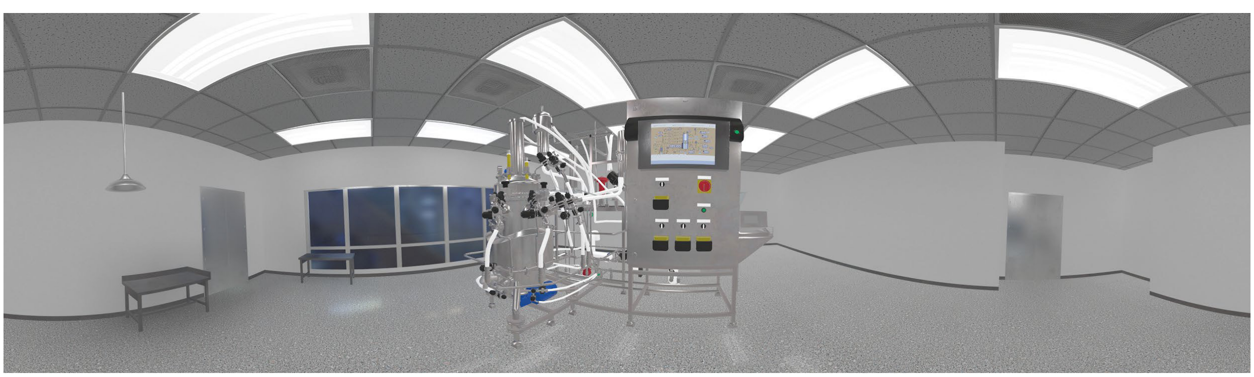

Figure 1 The bioreactor system in virtual reality, including the bioreactor, control unit, ancillary equipment, and utility pipes [Reprint with permission, [1]]

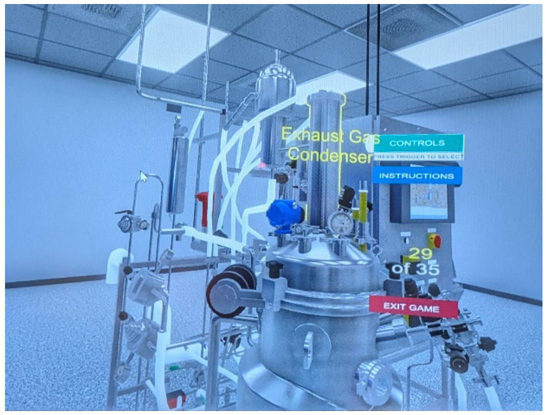

Figure 2 The bioreactor orientation VR: a sample scene when the exhaust gas condenser is selected in the virtual environment (viewpoint insider the VR)

2.2 Implementation in the *Environmental Sustainability for Industry* lab

Even though bioreactors are good subjects to teach environmental sustainability and biological processes, it is not feasible to use physical bioreactors in the *Environmental Sustainability for Industry* lab course due to facility and budget limitation. Therefore, the VR-based bioreactor initially developed for a bioprocessing lab was adopted and introduced. This VR lab module aims to introduce the configuration of a 30 L bioreactor system to the students, particularly those who have never seen such equipment before, and allow them to explore the virtual bioreactor at their own pace and in their own style.

Before the VR activity, students were provided a one-slide overview of the bioreactor system using pictures, along with a lab handout containing a list of bioreactor components (total 35) as well as 2D engineering reference diagrams of (1) top and side views of the bioreactor and (2) the air-oxygen supply system. The VR lab section took place at the Envision Center at Purdue University. Since there is only one HTC Vive headset available and to minimize motion sickness, each student was allotted up to five minutes in the VR environment. The entire lab module took two hours for both the overview prior to the VR activity and the five-minute-per-student VR experience. If more headsets were available, it would take less time to conduct the lab, or each student can have more time using the VR.

During the five-minute VR experience, each student was tasked to complete two activities listed in the lab handout: (1) explore as many bioreactor components as possible (total 35) by walking around the bioreactor and review the highlighted components in their eyesight, and (2) examine the internals of the bioreactor by walking into the bioreactor to observe and describe the component found. Students worked in pairs to complete the VR module, with one exploring the VR environment and the other monitoring their safety (e.g., maintaining awareness of physical boundaries and headset cables) and marking the identified bioreactor components in the lab handout.

2.3 Measures, participants, and data collection

There were 15 students in this lab course, and 13 students completed the VR lab module. The remaining two students chose to complete a video game version of the virtual bioreactor game without time restrictions due to known history of motion sickness with VR. At the end of the VR module, students submitted their filled lab handouts and completed a retrospective reflection questionnaire including Likert scale, dichotomous, and open-ended reflection items about their VR experience. The questionnaire prompted students to reflect on their perceptions both "before" and "after" the VR bioreactor activities.

Based on suggestions from literature [3, 15], the retrospective survey included items about participants' prior exposure to VR, perceived ease of use (e.g., "Was the VR technology easy to use?"), perceived usefulness (e.g., "Did [it] help you understand the materials?"), and open-ended reflections on the VR experience. The use of reflection in engineering education is a well-established method to prompt students to critically examine their learning experiences, connect theory to practice, and articulate personal growth [16]. In this study, surveys were administered via Qualtrics.

Both two types of student work – the lab handout and the reflection questionnaire - were graded based on regular rubric for lab attendance and reflection. Five months after the course ended, to understand student baseline engagement level and suggestions to a VR bioreactor lab module, student work was analyzed. Specifically, analysis focused on the lab handout completion as well as Likert scale responses on participants' prior exposure to VR and open-ended responses from the reflection questionnaires to answer the research question about engagement. Data analysis of the Likert scale responses regarding the perceived ease of use and perceived usefulness were not included in this paper due to the small sample size and irrelevant to the two research questions. This study only analyzed results from the 13 VR participants and excluded those two video game participants. No control group was included, as the department does not have the capacity to provide hands-on bioreactor lab experience as a control due to the high expense and facility limitation.

2.4 Data analysis

Our analysis drew on three data sources: (1) students' baseline familiarity with VR, captured through recalled prior experience in the retrospective reflection questionnaire; (2) students' lab hands-out activity, which involved completing a timed bioreactor component-identification task (quantitative performance data); and (3) and students' post-activity reflections in the retrospective reflection questionnaire (qualitative survey data). Quantitative scores were analyzed descriptively to assess task-directed engagement, while qualitative reflections were examined using thematic analysis [17, 18] to understand how students described and interpreted their learning experiences with the VR technology. The reflection responses were synthesized using thematic analysis. Results related to student engagement were analyzed and mapped into engagement levels, while students' challenges and suggestions for improvements are addressed in the Future Work section. The analysis of these data points was guided by the two research questions mentioned above.

3. Results

Research Question 1: How does virtual reality (VR) technology enhance student engagement in bioreactor learning?

To address this research question, we first examined students' baseline familiarity with VR technology. Students reported their pre-existing experience level by responding to the prompt in the retrospective questionnaire: "How often have you used virtual reality prior to this class?" The distribution of these responses is detailed in Table 1.

Table 1: Students' baseline familiarity with virtual reality technology

Question	Responses	Frequency
How often have you used virtual reality prior to this class?"	Never	4
	Occasionally (a few times a year)	9
Total responses		13

Students participated in a VR-based bioreactor intervention. This task required participants to explore as many of the 35 bioreactor components as possible and describe the component inside the bioreactor within a five-minute time limit. Data were recorded using a binary scoring system, where a "1" indicated successful identification, and a null entry represented a failure to locate the item. The aggregate identification counts per student, alongside student descriptions of the bioreactor internal structure, are presented in Table 2. The correct answer of the internal component is an agitator, but a propeller or a turbine are acceptable answers to someone new to bioreactor.

Table 2: Identification of Bioreactor Components through 3D Interaction and Visualization

Participants ID	Total number of components found (out of 35)	Student descriptions of the agitator inside the bioreactor*
EEE 01	26	"turbine"
EEE 02	25	"cylinder with squares on the side wall"
EEE 03	30	"a bank vault"
EEE 04	31	"Agitator"
EEE 05	31	"Turbine/propeller shape"
EEE 06	32	"Propeller"
EEE 07	34	"Turbine"
EEE 08	34	"Propeller"
EEE 09	34	"Turbine/Propeller"
EEE 10	30	"Cylinder with spokes"
EEE 11	33	"Long cylinder with spokes (propeller)"
EEE 12	30	"Propeller"
EEE 13	33	"Cylinder; turbine"

*Note. The agitator is the central mixing component of a bioreactor, responsible for circulating contents and maintaining uniform conditions. As part of this activity, students were not told what the agitator was but were asked to describe or name the component based solely on what they observed in the VR environment. The terms shown in the table reflect the different ways students interpreted and described this component.

Research Question 2: How do students describe and reflect on their learning experiences following engagement with VR technology in bioreactor learning?

This question focuses on how students describe and make sense of their learning after using the VR bioreactor module, drawing specifically on their written responses to the post-activity reflection questionnaire. This question examines the perceptions, interpretations, and meanings students express in these reflections to understand how the VR experience shaped their learning.

Engagement with VR

Students' reflections revealed mixed engagement, ranging from immersive, interactive experiences to enhanced visualization. These responses were organized into two subthemes: (1) Immersive Presence or a sense of "Being There"; (2) Interactive Exploration or Freedom to navigate VR. These themes reflect emotional and behavioral engagement, respectively, as reported in Table 3.

Table 3: Students' Reflections Mapped to Levels of Engagement

Level of Engagement	**Explanation**	**Example students Reflection**
Emotional (Affective) Engagement	Affective (emotional) engagement refers to students' feelings and emotional responses during the learning experience. In their reflections, students used affective language, such as enjoyment, real-life, and realistic, to convey their emotional connection to the experience.	"I enjoyed feeling as if I was actually visiting something that wasn't on campus. Like a field trip." "Being able to identify the parts of a bioreactor in a real-life setting" "Being able to see inside the reactor without interference, which is impossible in real life. Also being able to see the parts from all angles."
Behavioral Engagement	This theme captures behavioral engagement, focusing on students' ability to move around and interact with the environment. Students used specific words to describe their behavioral engagement, such as "walking around and seeing" and "walking through and inspecting.	"I could *walk* through the reactor and *inspect* it up close, even *inside* the reactor." "I enjoyed walking around and seeing aspects close up."

4. Discussion

Students treated the VR bioreactor exercise as a game-like challenge, aiming to identify all 35 components even though the task only required recognizing as many as possible. As shown in Table 2, early participants identified 25 and 26 components, which was notable; however, later participants identified more, with some identifying up to 34. Because students took turns to complete the exercise one at a time, they inevitably shared their lived experiences with peers, which may have contributed to later participants scoring higher. This sharing of impressions within the immersive VR environment may have increased confidence and yielded better ideas for navigating the bioreactor, illustrating how VR technology can support engagement. Additionally, literature shows possible shielding of distractions from the physical workplace in the VR environment [19], which may support attention and engagement.

When discussing the bioreactor internal components, students used a range of descriptors that reflected differing levels of conceptual framing. One identified the component using the disciplinary term *agitator*, indicating alignment with formal engineering language. Others described it as a *turbine* or *propeller*, drawing on familiar mechanical analogies to convey its function. A third group relied on visual or geometric descriptions (e.g., "a cylinder with spokes"), while a small number (1) used metaphorical labels such as "bank vault." Collectively, these varied expressions suggest a progression from surface-level visual recognition to functional analogy and, for some students, disciplinary understanding of the system component.

Students' reflections further indicate that the VR bioreactor environment supported both affective and behavioral engagement, signifying a shift from passive observation to active, discovery-based learning. By using descriptors such as "feeling like I was actually there" and likening the experience to a "field trip," students demonstrated a high degree of immersive presence, transforming the bioreactor from a complex concept into a tangible, lived experience.

Furthermore, the behavioral engagement evidenced by students "inspecting" and "walking through" the reactor highlights a level of interactivity similar to hands-on labs. Being able to inspect components "up close" and even "inside" allows for a granular understanding of engineering design, such as the positioning of agitators, that is essential for optimizing energy efficiency and process sustainability. These results corroborate recent VR engagement studies in engineering and sustainability education, which emphasize immersive presence, realism, and interactivity as key drivers of student engagement [1, 3, 8, 13]. Notably, the action of "walking into" the reactor is not feasible in a real-world scenario, the unique benefit of VR for observing phenomena that are inaccessible in hands-on labs.

5. Limitations

This study did not include a control group because a hands-on bioreactor lab experience is not affordable and feasible within the department. Therefore, it was not possible to compare the VR bioreactor lab experience with a traditional hands-on bioreactor lab experience. Although two participants completed a video game version of the virtual bioreactor, they were not used as a control group for two reasons: (1) the sample size of the video game group (n = 2) is too small, and (2) the purpose of this study is not to compare VR-based learning to video game-based learning. Additionally, this study only focused on students' baseline familiarity with bioreactor technology, their ability to identify bioreactor components, and how they reflected on and described their experience and engagement with the bioreactor. However, considering it was only a five-minute VR module, the concepts of familiarity, identification, and description capture only surface-level exposure and declarative knowledge, rather than deeper conceptual understanding, procedural competence, and embodied skill development, which are central to authentic bioprocessing practice. The study's measures do not account for how students apply knowledge in novel situations, respond to unexpected system behaviors, or manage real-world safety constraints and physical interactions with equipment. Consequently, future studies would benefit from the use of more rigorous, validated instruments that assess aspects of student learning and experience across virtual and physical learning environments.

VR technology sometimes misses crucial aspects of real-life activities, particularly tactile feedback, environmental awareness, and the physical consequences of actions. While VR excels in visual and auditory immersion, it often fails to replicate the full sensory experience and safety risks inherent in physical environments.

6. Future work

One major challenge of the VR experience reported by students was motion sickness, which is a well-documented challenge of VR. To address this challenge, we plan to upgrade the bioreactor into Augmented Reality (AR) or Mixed Reality (MR) with Meta Quest 3 headsets. This transition is expected to reduce motion sickness while enabling additional functionality, such as zooming in and out to support more detailed interaction with the bioreactor. AR or MR bioreactor orientation and exploration activities could be implemented not only in this lab course but also in other lecture-based environmental, biological, and chemical engineering courses to support instruction of bioreactor concepts.

Another improvement concerns assessment within the virtual environment. In the current VR setup, the system tracks only the total number of identified components, rather than recording which specific components were found or the order in which they were identified. As a result, the students were required to work in pairs to manually track progress. Future versions of the platform should include automated tracking of both the sequence and identity of components identified by each student. Additionally, different interaction modes (e.g., review mode, quiz mode) could be incorporated into the AR or MR environment to support learning goals.

In the long term, a Design of Experiments (DOE) fermentation lab module will be developed in MR. DOE is a core topic in this laboratory course, yet it is difficult to implement in person due to the high cost and labor-intensive nature of fermentation-based bioreactor DOE experiments. An MR-based bioreactor would make a fermentation DOE lab module feasible. Currently, only the video game version of the virtual bioreactor is available online since the VR/AR/MR version is undergoing revision, which will be available online once updated.

7. Conclusion

This paper presents how VR enhanced student engagement and learning in an environmental engineering laboratory through 30 L bioreactor activities. Data were collected from student lab handout activities and a post-activity retrospective reflection questionnaire. Student performance in the lab handout activity, along with post-activity retrospective reflections, served as indicators of learning engagement. Results showed strong engagement, with 85% of participants identifying at least 30 of the 35 components, demonstrating that the VR environment effectively supported focused attention and purposeful interaction. These findings hold particular significance for environmental engineering and sustainability education, where students must be able to visualize and interpret processes that are often hidden within closed, hazardous, or large-scale systems. Traditional instruction, which relies heavily on static diagrams or brief observational opportunities, offers limited access to such systems and can restrict meaningful engagement. By rendering these otherwise inaccessible processes visible, navigable, and safe to explore, VR provides an immersive and repeatable learning experience that helps students build clearer conceptual understanding of the core operations that underpin environmental sustainability. Additionally, VR also provides students with access to interactive intermediate scale bioreactor experience, that is typically too expensive to implement in most environmental engineering lab curricula.

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