Assessing the Impact of the Non-Physical Laboratory Approach on Open-Ended Environmental Laboratory Practice

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Abstract

This study evaluates the impact of integrating virtual/online open-ended laboratories (OEL) into environmental engineering courses for undergraduate civil engineering students. Incorporating OEL allows students to engage in hands-on, problem-based learning activities that simulate real-world environmental challenges. This article focuses on the benefits, design considerations, and implementation strategies for integrating open-ended environmental laboratories into the undergraduate civil engineering curriculum, enhancing students' critical thinking, teamwork, and ability to develop sustainable engineering solutions. The study examines the implementation of problem-based laboratory techniques over four consecutive cohorts (n=229), capturing the transition from traditional OEL to fully online OEL during the COVID-19 Movement Control Order (MCO) and partially at subsequent post-pandemic conditions. Despite an initial decline in student learning performance during the first year of online OEL, subsequent years showed significant improvement. This trend aligns with student perception surveys, which reflect positive outcomes from the online OEL experience. One of the positive outcomes observed was the adaptability to future challenges. The experience of adapting to online learning environments prepared students for future professional scenarios that may require remote collaboration and virtual problem-solving. A notable insight from the partially online laboratory courses is the expanded opportunity to explore interactive virtual lab platforms and utilize remote data collection methods, enriching the teaching paradigm. Integrating open-ended laboratories in environmental engineering aligns with the Sustainable Development Goals (SDGs) and equips students with essential skills to address global sustainability challenges effectively.

Keywords: Outcome-based Education, Engineering Education, Open-ended Laboratory, Online-Lab, Perceptions, Post-COVID-19.

Introduction

In an engineering or technical program, practical and hands-on experiences during laboratory courses help students develop a multidisciplinary understanding of the topics. These experiences also allow students to apply theoretical knowledge in practical settings, leading to an enhanced learning experience. Meeting the requirements of the Engineering Accreditation Council (EAC) in Malaysia, the criteria stress the importance of inclusive education for laboratory experiments. This approach aims to produce graduates who have a strong theoretical foundation, are proficient in practical applications, and can understand complex real-world situations. They need to be able to design and conduct experiments, analyze and interpret data effectively, and work well in group settings (Zaiton et al., 2013).

Laboratory courses usually involve straightforward and quantifiable assessment of exercises and assignments (Samarakou et al., 2014). In these courses, the instructor provides students with guidelines and instructions for conducting experiments or completing assignments, which are then graded by the educator or the system. However, there is a need to better align this traditional laboratory approach with the current context of outcome-based learning environments. As a result, a recent shift has been towards upgrading laboratory courses' teaching and learning methods to open-ended laboratories (Kofli & A. Rahman, 2011). Open-ended laboratories (OEL) go beyond the traditional approach by giving students more autonomy and freedom to explore and experiment. Additionally, OEL activities are not limited to engineering courses but are applicable across various disciplines. Wilcox and Lewandowski (2016) examined the impact of OEL in undergraduate laboratory physics courses on students' epistemologies and expectations. Their findings revealed that OEL positively influenced students' understanding of the nature of experimental physics and resulted in significantly higher scores compared to students in courses using only traditional guided labs, both pre- and post-instruction ($p \ll 0.01$).

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Implementation of online-OEL supported by the Problem-Based Learning educational model, that emphasizes student-centred learning through engagement with authentic, ill-structured problems. In combination to Kolb's Experiential Learning Theory, it involves four-stage learning cycle: experience, reflective observation, abstract conceptualization and active experimentation, particularly when transitioning between traditional and virtual laboratory formats (Kolb, 1984)

Particularly in environmental engineering laboratories, open-ended approaches are vital to bridge the gap between theory and real-world applications, encouraging students to think critically, design their experiments, and develop innovative solutions related to environmental problems. Some of the key characteristics of open-ended laboratories are based on the aspect of problem-based learning, whereby learners were challenged to think critically, provide creative solutions and have freedoms to design their experiments. Furthermore, according to McCrory et al. (2020), laboratories have the capability for sustainability transition transformation approaches and provide a basis for case-based comparisons. Engineering education is changing rapidly due to the rapid growth of new technologies and the adoption of modern education methods (Kim et al., 2023); hence online learning in engineering is not new and can be applied in courses like laboratory subjects. The COVID-19 pandemic has also enforced a global need for online teaching/learning opportunities. UNESCO states that more than 1.5 billion students worldwide have been affected due to closures and educational changes (UNESCO, 2022). Various issues negatively influenced online engineering education, including logistical/technical problems, learning/teaching challenges, privacy and security concerns, and insufficient hands-on training (Asgari et al., 2021).

Therefore, this paper examines the impact of online teaching on the OEL of environmental engineering laboratory courses, which are typically taught through face-to-face instruction. This study investigates the insights gained from empirical evidence and provides recommendations for addressing the challenges posed by COVID-19 until the recovery/post-pandemic period.

Methodology

The study aimed to analyze the impact of online teaching on the environmental engineering laboratory course. It assessed the effect of online teaching and learning of lab course during the Movement Control Order (MCO) and the transition to a combination of physical and online laboratory approaches on the learning experiences and outcomes of final-year undergraduate students taking the civil engineering environmental laboratory course over four consecutive cohorts. The cohorts were divided into three categories (Table 1).

Table 1. Cohort Category

Cohort ID	Categorisation
Cohort A	Physical Laboratory
Cohort B1 and B2	Hybrid Physical and Virtual Lab
Cohort C	Physical Laboratory

The laboratory sessions divided undergraduate students into small groups of four to five members. The purpose of this group arrangement was to encourage effective communication, teamwork, and peer discussions among the students throughout the laboratory investigation process until the technical journal report submission. The Environmental Laboratory introduced the open-ended lab (OEL) format during the regular course, which has been compared to traditional lab courses in our previous work (Bolong et al., 2014). As part of ongoing curriculum restructuring, and continuous quality improvement (CQI), assessments for Course Outcomes 4 (CO4) and 5 (CO5) were introduced starting with cohort B1. The course spanned fourteen consecutive weeks, with each session lasting three hours, focusing on the learning outcomes outlined below (Table 2).

Table 2. Course Learning Outcome (CO)

CO ID	Learning Outcome
CO1	Conduct experiments following standardised procedures and techniques to address environmental problems of water quality, air pollution, and noise pollution
CO2	Evaluate and interpret the experimental data; with proper justification on the experiments outcome
CO3	Effectively communicate technical concepts, procedures, and results to peers and instructors, using precise and appropriate scientific terminology
CO4	Function effectively as an individual and as a member or leader of a team
CO5	Adhere to lab protocols, including proper attire, maintaining cleanliness and adhering to safety regulations.

Due to the educational institutions were closed due to the coronavirus pandemic and the Movement Control Order (MCO) enforcement, a modified approach combining partial physical laboratory work and online components was implemented to adapt to the situation. It includes online video demonstrations of relevant instruments, utilizing secondary data from available local websites (such as published air quality data based on collection stations), and utilizing mobile phones for noise measurement in students' respective houses. Starting from chort B1, CO4 is evaluated using peer assessment, highlighting its relevance to collaborative learning and critical assessment between members. Whereas CO5 employs online test after reviewing video resources based on laboratory safety and protocols to ensure foundational knowledge prior practical activities. Table 3 summarizes the transition and changes in the implementation of the OEL.

Table 3. Comparison of Laboratory Course Delivery and Assessment Approaches Between Cohorts A, B and C

Course outcome	Cohort A (n=53)	Cohort B1 (n=53) and B2 (n=56)	Cohort C (n=67)
CO1	Laboratory work (Experiment design)	**Secondary data and lab work**	Laboratory work (Experiment design)
CO2	Discussions and presentation (physical)	Discussions and presentations **(online)**	Discussions and presentation (physical)
CO3	Written report in journal format	Written report in journal format	Written report in journal format
CO4	Not applicable	Peer assessment and observation	Peer assessment and observation
CO5	Not applicable	Safety test	Observation and Safety test

The study employed a combination of direct and indirect measurement approaches to assess learners' achievement and investigate the effects of transitioning from a physical to a partially online laboratory system. The analysis of the factors listed in Table 4 provided a comprehensive empirical evaluation of how the instructional methods influenced the attainment of course outcomes and the effectiveness of implementation strategies.

Table 4. Factors employed for data analysis

Data analysis factor	**Measurement indicator**	**Quantification Unit**
Course learning outcomes (COs)	Student continuous assessment. *direct measurement method	Evaluation marks indicator from 'Very poor' to 'Very Good.' *Very poor: 0 to 19 Poor: 20 to 39, Satisfactory: 40 to 59 Good: 60 to 79, and Very good: 80 to 100*
Student perception feedback (CO perception)	Based on self-rating on the course outcome questionnaire. **indirect measurement	Likert scale: rate 1 to 4 (1-poor and 4-Very good)
Course evaluation	The institution's quality academic survey (PK07) that conducted to gather feedback from students regarding the implementation of the course. **indirect measurement	Item rating Likert 1 to 5 and averaged based on: 1) Facility (equipment and learning management) 2) Learning outcome (knowledge, competency) 3) Soft skills attainment (communication, critical thinking, life-long learning, etc.)

The direct measurement used the attainment of course outcomes to measure student performance. Course outcomes, also known as learning outcomes or learning objectives, specify the knowledge, skills, or competencies that students are expected to acquire or demonstrate by the end of a course. The direct measurement of course outcomes involved assessing students' performance through various means such as practical assessments, laboratory reports, lab exams/tests, and observation/performance assessments. These assessments evaluated students' understanding, application of concepts, practical skills, and critical thinking abilities.

In addition to the direct measurement methods, this study incorporated two indirect measurement approaches to gather student feedback and perceptions. These methods included student perception feedback surveys and course evaluation surveys, which provided at the semester's end. The perception survey utilized an average arithmetic calculation of all rating scales to obtain a comprehensive overview of student evaluation.

The first indirect measurement method was the student perception feedback survey, which assessed students' self-perception of their attainment in the lab course. This survey allowed students to reflect on their achievements and provide feedback on their learning experiences. The survey captured their subjective perceptions of their performance and progress in meeting the course outcomes, in a likert-scale rating from 1 to 4, represented based on poor (1) to very good (4), coded comparable to grade pointer expected for respective outcomes.

The second indirect measurement method involved administering the university's quality academic course survey, a compulsory evaluation completed by all students. This survey provided a broader perspective on the course covering aspects such as teaching quality, course materials, assessments, and overall satisfaction. Together, these methods offered a comprehensive and structured view of student experiences, which were then analyzed qualitatively to enrich the study's findings and ensure consistency in interpreting the data.

Results and Discussion

The analysis of quantitative data regarding student performance in open-ended environmental laboratories is presented in Figure 1a (CO1-3) and Figure 1b (CO4-5). The achievement of course outcomes is influenced by the assessment approach employed. Hence a comparison was made between the attainment of the different cohorts based on the assessment of course outcomes. In open-ended laboratories (OEL), certain key elements are crucial. These elements include delivering laboratory assessments that enable students to design and execute experiments, analyze and interpret data, and collaborate effectively within a group setting (Azida et al., 2018). Therefore, this study measured the attainment of course outcomes (COs) by assessing students' knowledge, skills, and competencies in conducting water quality testing, air quality determination, and noise measurement; in terms of, i.e., CO1-experimental design, CO2-analysis, CO3-journal, CO4-team, and CO5-safety. The course implemented an open-ended laboratory approach, wherein students were tasked with designing and executing their experiments centered around environmental topics, specifically focusing on water, air, and noise. These learning experiences aim to equip students with the necessary skills to tackle the intricate challenges associated with sustainable infrastructure development and environmental measurement impact.

The open-ended laboratory approach aimed to foster students' critical thinking skills and encourage independent problem-solving by requiring them to develop testing instructions and strategies while demonstrating appropriate reasoning, knowledge background, and logical justification. While designing their experiments, students were also required to consider and adhere to relevant testing standards and guidelines. The laboratory work played a crucial role in helping students understand environmental issues by providing them with hands-on experiences in conducting experiments and tests related to real-world problems such as water quality, air, and noise pollutant issues. Specifically, in determining water quality testing and analysis, assess air pollution and noise problems by correlating to the required local and community standards and regulations. This approach allowed students to apply their theoretical knowledge and practical skills to address environmental challenges.

As shown in Figure 1a, for the evaluation of experiment design (CO1), there was an observed increase in the 'good' achievement trend, despite the challenges posed by online work. Cohort C demonstrated a return to normalcy and adaptation to the physical learning environment. In the case of lab analysis (CO2), attainment in the 'very good' category was initially high during ordinary situations. However, during partial lab work due to the Movement Control Order (MCO) (for cohort B1), the attainment became more varied, possibly due to reduced engagement among learners and the course instructor compared to face-to-face labwork (before MCO).

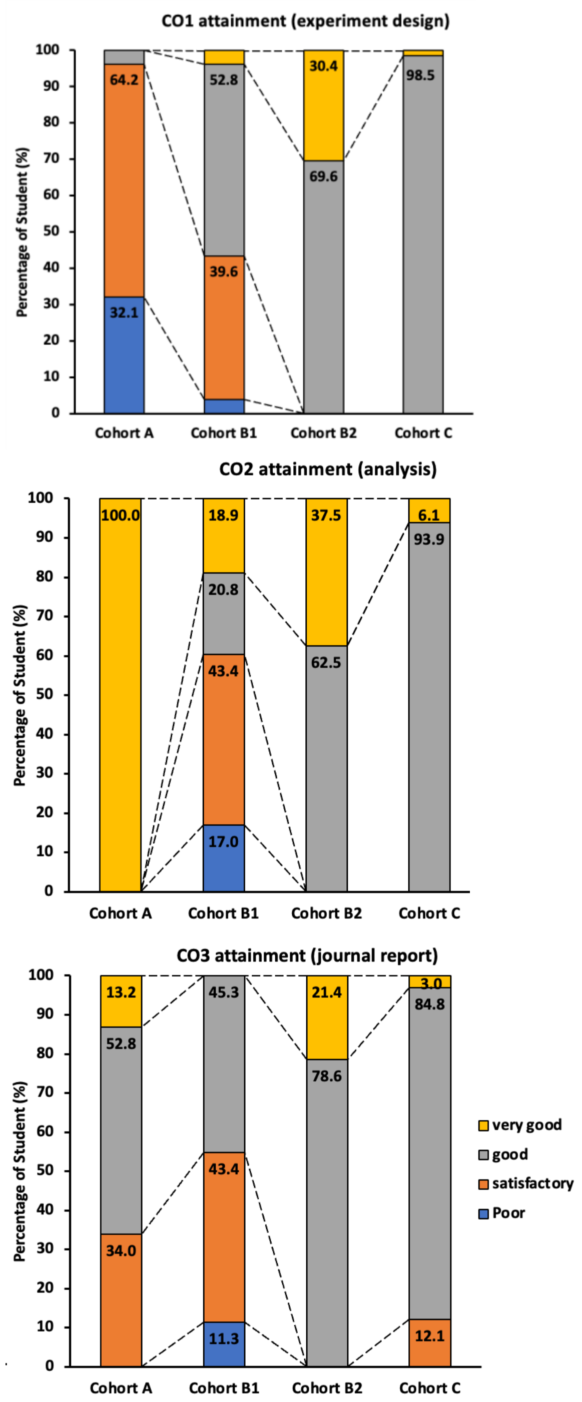

Figure 1a. Attainment of different cohorts based on course outcomes assessment (CO1, CO2, CO3).

Nevertheless, most students still achieved the 'good' category and showed improvement in subsequent years. Interestingly, cohort B1, which experienced partial physical lab work, attained higher levels of 'very good' compared to the following year of physical lab work (cohort C), indicating a potential adjustment period during the post-pandemic phase. Regarding the course outcome for the journal report (CO3), most students achieved the 'good' category. Still, there was a slight reduction during partial physical lab work (cohort B1), followed by an increase in the subsequent year.

Considering the three course outcomes (CO1, CO2, and CO3), it is evident that the initial online lab implementation resulted in lower and more varied levels of attainment compared to the previous typical year. Hands-on laboratory activities reinforce learning, and transitioning to virtual or online classes presents challenges (Schneider et al., 2022). However, improvement was observed in the subsequent years. A hybrid learning approach, where students partially engage in on-campus laboratory experiences, work with equipment and components, and collaborate in teams, has shown positive results like other work (Sarwono and Lyau, 2023). Although the modification of fully hands-on laboratory work and physical engagement slightly affected student learning, improvements were observed once the lab implementation returned to regular, necessitating adjustments from both lecturers and students. Another study by Noor et al. (2023), made a similar observation, noting that most students performed well in the course after adjustments to their assessment methods and procedures. Additionally, implementing open-ended labs during partial virtual/lab as in this work, such as utilizing secondary data from meteorological stations and conducting noise measurements using mobile devices, presented opportunities for more creative assessments. This approach challenged teachers and learners to think critically beyond traditional equipment-based laboratory experiences.

Whereas for Figure 1b, the assessment of CO4 and CO5 was conducted only for the most recent three cohorts (B1, B2, and C), as program syllabus revision was implemented. Regarding CO4, using peer assessment and observation during partial lab work improved students' attainment, with the majority achieving the 'good' category. This indicates the effectiveness of peer assessment and remarks in enhancing students' performance and understanding of the subject matter.

Interestingly, concerning CO5, which pertains to lab rules and safety, there was a reduction in attainment in the 'very good' category. This could be attributed to the assessment method used for the online safety test, which may have provided a better grasp of the concepts compared to the actual safety test and observation during lab implementation. To address this, it is suggested to consider incorporating more practical and hands-on assessments for lab rules and safety to ensure a comprehensive understanding among students. This could involve conducting physical safety tests and providing opportunities for direct observation during lab sessions. By doing so, students will have a more accurate and practical understanding of lab rules and safety measures, leading to improved attainment in this course outcome.

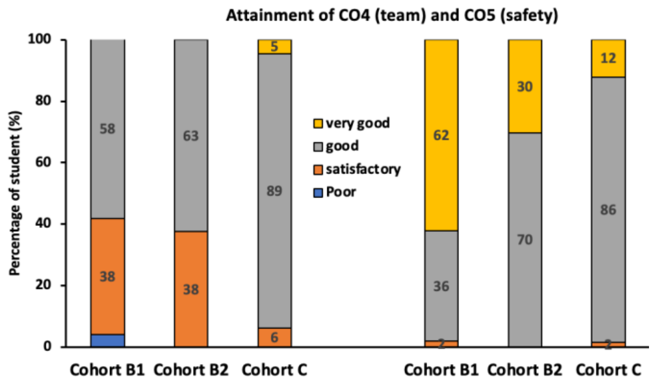

Figure 1b. Attainment of Cohort B and C; based on course outcomes assessment (CO4, CO5).

Comparing the results of indirect assessment through the Student Perception Feedback Survey with the students' learning attainment and course evaluation survey (PK07) revealed exciting trends, as depicted in Figure 2 and Figure 3.

Figure 2 illustrates that during the first year of the Movement Control Order (MCO), Cohort B1 experienced a decrease in students' self-achievement compared to the previous year (cohort A). However, Cohort B2 and Cohort C improved their confidence levels in the following years, as evidenced by an increased average rating.

Moreover, the student's course evaluation survey (Figure 3) demonstrated a constant improvement in feedback ratings. Students provided higher and more positive ratings, indicating an enhanced perception of the overall course. The implementation of open-ended laboratories (OEL) requires students to possess high levels of self-motivation and independence, indirectly cultivating their professional engineering skills (Haron et al., 2013). A comparative study between traditional and open-ended laboratories in the learning process has also shown that OEL improves students' understanding of the subject matter more effectively than conventional laboratories (Rahman et al., 2011). Additionally, OEL promotes student independence in learning, fosters creativity in problem-solving, and enhances teamwork and communication skills (Gowtham et al., 2020).

These findings suggest that while there was a temporary setback during the initial MCO year, subsequent cohorts demonstrated increased self-achievement and more positive perceptions of the course. It is crucial to analyze these trends further and identify the factors contributing to the observed improvements to enhance future educational practices.

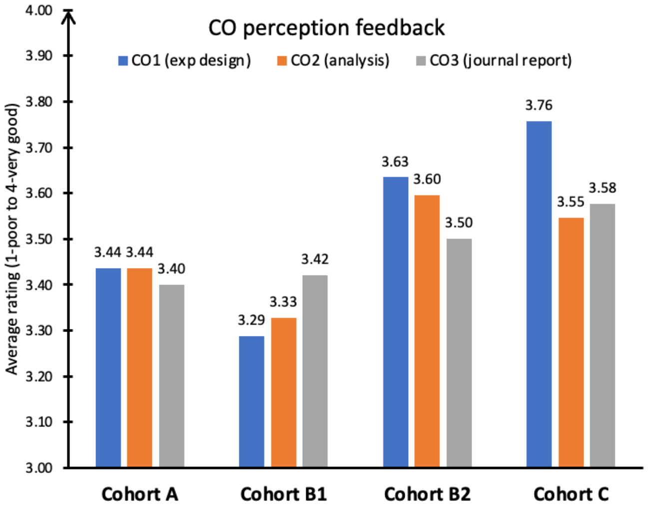

Figure 2. Student feedback survey on self-perceived achievement of course outcomes (COs).

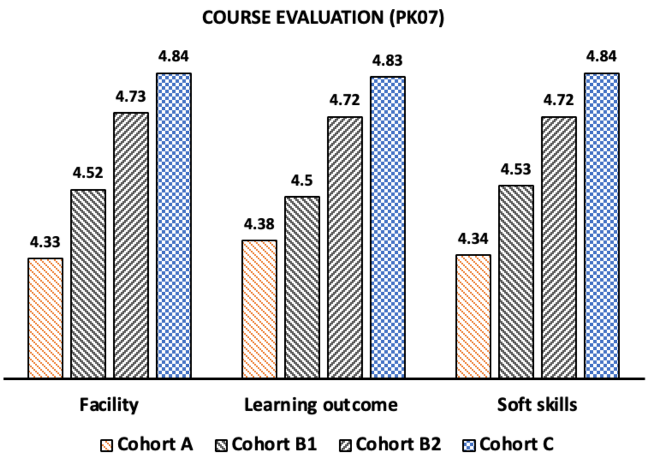

Figure 3. Course evaluation survey on facility quality, learning outcome achievement, and self-assessment of soft skills development.

Conclusion

Despite challenges and various limitations in the Open Ended environmental laboratory implementation for civil engineering undergraduates due to the disruption of the COVID-19 pandemic, the institution continued to ensure the best learning opportunities and strive for sustainable recovery. The empirical insight from the outcomes and experience in this study generally shows that the initial online or non-physical OEL (during MCO) implementation resulted in lower and more distributed attainment than the previous normal year (before MCO). However, improvement was observed in the later years when the lab implementation adjusted and returned to normal, highlighting the importance of hands-on laboratory work and physical engagement. Adjustments from both lecturers and students were necessary during the transition. Additionally, implementing open-ended labs during partial lab work fostered creative assessments and challenged critical thinking skills beyond traditional equipment-based laboratory experiences. Quantitative data analysis in open-ended environmental laboratories provides valuable insights into student performance and course outcomes. The assessment approach influences the attainment of course outcomes used.

Additionally, this study also holds transformative potential not only for environmental engineering but also for the broader spectrum of engineering education. The study highlights the ongoing relevance of virtual lab environments and adaptive pedagogical strategies in today's educational landscape. As educational needs and technological capabilities continue to evolve, integrating diverse, flexible, and globally-informed approaches remains critical for equipping students with practical skills in a digital-first world. The findings also contribute to the broader discourse on modernizing lab-based learning, demonstrating that innovative virtual solutions play a vital role in addressing accessibility and fostering hands-on learning experiences across diverse educational contexts. As educational institutions increasingly embrace technology-driven solutions, hybrid models offer a sustainable framework to enhance engagement, promote interdisciplinary learning, and equip students with the adaptive skills necessary for a rapidly evolving world. Emphasizing these possibilities aligns the study with emerging trends in educational technology, underscoring its significance in modernizing engineering and broader educational practices.

To further enhance student learning in open-ended environmental engineering laboratories and the inclusiveness of continuous quality improvements, the following was recommended:

- The positive insight in online lab implementation provides a better opportunity to explore interactive laboratory and virtual lab platforms and utilize remote data collection methods.
- Strengthen practical engagement by reinforcing hands-on laboratory work through active participation and exploration to deepen students' comprehension and skill development.
- Innovative assessment methods should be embraced by exploring diverse approaches to evaluation. For instance, virtual environmental monitoring simulations allow students to replicate environmental monitoring scenarios using tools such as GIS-based platforms. Students are required to design and execute virtual experiments to predict the outcomes of environmental changes, followed by submitting a written report or video explanation. However, this approach necessitates access to computational devices and specialized software, which can be costly and may present challenges in resource-constrained settings.

- Continuously improving and adapting the strategies based on student feedback and changing education needs is vital. Regularly reviewing the effectiveness of the assessment methods and making necessary adjustments will ensure the course remains relevant and impactful to students.
- Incorporating open-ended environmental laboratories into the undergraduate civil engineering curriculum requires educators to reimagine their teaching methods, providing students with meaningful experiences that prepare them for the complex challenges of sustainable infrastructure development and environmental stewardship. By fostering sustainable engineering practices, these open-ended laboratories contribute to attaining the Sustainable Development Goals (SDGs).

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Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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