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Original Research Article

Application of Team-Based Learning in Green Infrastructure Education: An Active and Interdisciplinary Approach to Sustainable Engineering

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ABSTRACT

Team-based learning has been increasingly applied in engineering education as an active learning methodology to enhance student engagement and interdisciplinary collaboration. This study evaluates the implementation of team-based learning in a graduate-level course on Green Infrastructure and analyses its impact on student performance and perceptions. The methodology involved individual assessments, team discussions, and a final Class Evaluation Form to measure student engagement and learning outcomes. Results indicate that team-based assessments significantly outperformed individual assessments, reinforcing the effectiveness of peer learning. Student's feedback highlighted high engagement, the topic's relevance, and the instructor's essential role in facilitating discussion. These findings suggest that team-based learning fosters a more interactive and meaningful learning environment, making it a valuable approach for engineering education, particularly in interdisciplinary and sustainability-focused courses. Future studies could explore long-term knowledge retention and professional skill development through team-based learning.

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KEYWORDS

Team-Based Learning, Green Infrastructure, Active Learning, Engineering Education, Sustainability, Collaborative Learning.

INTRODUCTION

Sustainability and Engineering Education

Recent studies have highlighted the growing importance of teamwork as a core professional competency in engineering and related fields. For example, [1] show that collaborative skills are increasingly demanded by employers due to the complexity and interdisciplinarity of contemporary engineering projects. Complementarily, [2] evince that students who are exposed to structured teamwork activities during university exhibit improved communication, problem-solving, and professional preparedness.

Beyond fostering teamwork and critical thinking, engineering education must also address contemporary global challenges. Among these, sustainability contitues one of the most pressing issues in problem-solving [3]. In this context, the engineering profession plays a core role in responding to these emerging demands by drawing on knowledge and competencies from multiple disciplines and advancing innovative areas such as resource productivity, energy efficiency, integrated systems design, and biomimicry, that is, nature-inspired design [4]. The intricate, interdependent nature of sustainability challenges requires a multidisciplinary, collaborative approach to develop effective, long-lasting solutions. Recognizing this need, the United Nations General Assembly adopted the Sustainable Development Goals (SDGs) in 2015, establishing “a shared blueprint for peace and prosperity for people and the planet, now and into the future” [5].

Green Infrastructure and Ecosystem Services

Increasing complexity of urban environmental challenges has driven the adoption of Green Infrastructure (GI) as an integrated solution to enhance city resilience and sustainability. These infrastructures combine natural and engineered elements to provide multiple benefits, including stormwater management, improved air quality, and urban heat mitigation [6]. Additionally, they play a crucial role in biodiversity conservation and restoring natural cycles in urban areas, transforming impervious spaces into ecologically functional environments. In engineering, implementing these solutions requires an interdisciplinary approach that integrates technical and ecological knowledge to optimize performance and reduce maintenance costs [7]. Thus, GI addresses contemporary environmental challenges and creates opportunities for better integration between the built environment and natural systems, fostering more sustainable and resilient cities. Several developed and developing countries are already using this approach to obtain economic, sociocultural, and environmental advantages [8].

GI encompasses a broad range of nature-based and hybrid solutions implemented in urban environments, including vegetated roofs and façades, rain gardens, bioretention systems, infiltration swales, detention basins, permeable pavements, and green streets, designed to enhance environmental performance and urban resilience. In recent years, the intensification of climate change impacts has led cities worldwide to seek adaptive strategies to mitigate environmental risks while strengthening socioecological resilience. In this context, GI has emerged as a multifunctional approach that integrates ecological processes into urban planning, offering benefits beyond climate adaptation, including improvements in environmental quality and human well-being [9].

By incorporating natural elements into the built environment, GI plays a key role in providing ecosystem services, understood as the ecological functions and processes that directly or indirectly support human life and societal development. These services include, among others, regulating hydrological cycles, moderating climate, enhancing urban biodiversity, and improving air and water quality—all of which are fundamental to sustainable urban systems [10].

Moreover, GI implementation is closely aligned with achieving several SDGs. Its multifunctional character contributes not only to goals directly associated with urban sustainability and climate action, such as Sustainable Cities and Communities (SDG 11) and Climate Action (SDG 13), but also to broader objectives related to infrastructure development, ecosystem conservation, public health, social equity, and water security. As such, GI represents a strategic pathway for promoting integrated, resilient, and sustainable urban development across both developed and developing regions [11].

Team-Based Learning in Engineering Education

Given the complexity and interdisciplinary nature of GI, engineering education must equip students to analyse, discuss, and develop solutions collaboratively. In this regard, Team-Based Learning (TBL) emerges as an effective pedagogical strategy, particularly in graduate-level engineering courses. Active learning methodologies significantly enhance content comprehension, with TBL featuring among the most widely accepted by students [12].

Recent studies show that competitive and collaborative team-based learning approaches significantly improve students' engagement, motivation, and retention of core engineering concepts [13]. This methodology also strengthens essential professional skills, particularly teamwork and communication, and has been widely accepted by students as an effective active learning strategy in engineering education [14]. Higher test scores and a consistent reduction in failure rates were observed in mechanics of materials courses when TBL was integrated, compared with traditional lecture-based instruction [15].

Team-based approaches foster a more dynamic and accessible learning experience than individual study, as reflected in student performance assessments. Moreover, the instructor's role is crucial in facilitating discussions, providing feedback on group work, clarifying doubts, and synthesizing key concepts. Each educator is responsible for engaging students to help them develop their full potential and meaningfully contribute to sustainable development. By integrating TBL into GI teaching, students engage in collaborative problem-solving, reinforcing their ability to address real-world engineering challenges while developing essential teamwork and critical thinking skills [16].

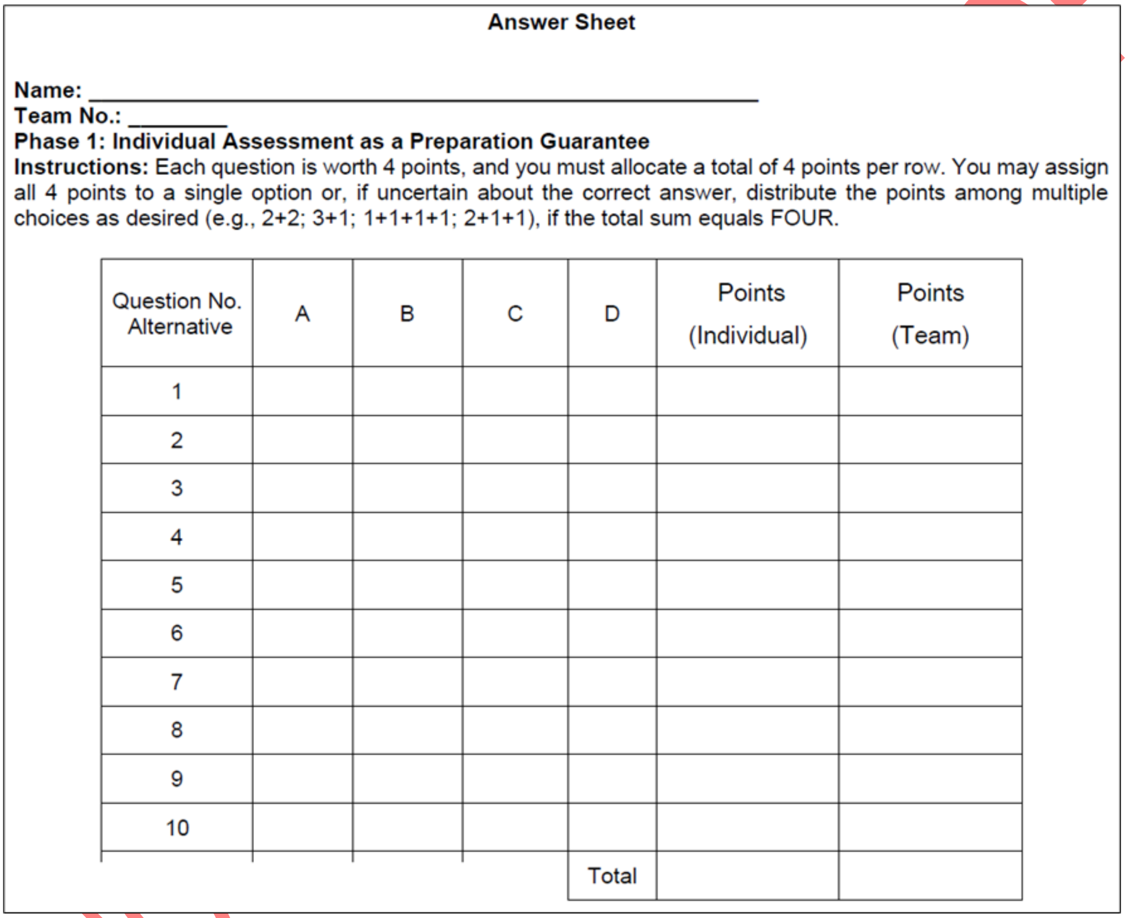
Hence, this study reports on the application of TBL as an assessment method in a graduate-level environmental course and evaluates its effectiveness in enhancing student engagement, interdisciplinary collaboration, and understanding of GI concepts. We analyse the impact of TBL on student performance, teamwork dynamics, and the ability to apply theoretical knowledge to practical engineering challenges, contributing to research on active learning methodologies in sustainable engineering education.

Although previous studies have investigated TBL in engineering education, most focus on general learning outcomes or single-course applications, without explicitly linking collaborative learning to complex, interdisciplinary topics like GI. In contrast, the present study advances the literature by applying TBL to the teaching of GI concepts, explicitly addressing their interdisciplinary nature and real-world engineering challenges. Additionally, this work provides empirical evidence from a graduate-level engineering context, thereby extending existing research that has primarily focused on undergraduate or non-environmental engineering courses. Thus, this study not only applies TBL to a sustainability-oriented engineering context but also provides empirical evidence that collaborative assessment enhances understanding of complex environmental systems, reinforcing its relevance to sustainability-focused engineering education.

METHOD

TBL is a methodology that requires students to prepare in advance for classroom activities based on the instructor's assigned materials. Developed in the 1970s by Larry Michaelsen, this approach can be applied to groups of over 100 participants and to smaller groups of up to 25 students [17]. The first step in TBL classroom implementation is forming student groups, typically consisting of 5 to 7 members. Ideally, the instructor should randomly assign students to ensure greater diversity within each group, preventing the formation of teams based on personal bonds or pre-existing relationships, which could influence group dynamics [18].

The next step involves assessing students' preparation through a readiness assurance test (RAT), which verifies and ensures their level of preparedness [18]. Figure 1 presents the answer sheet used for this evaluation.



Answer Sheet

Name: ____

Team No.: ________

Phase 1: Individual Assessment as a Preparation Guarantee

Instructions: Each question is worth 4 points, and you must allocate a total of 4 points per row. You may assign all 4 points to a single option or, if uncertain about the correct answer, distribute the points among multiple choices as desired (e.g., 2+2; 3+1; 1+1+1+1; 2+1+1), if the total sum equals FOUR.

Question No. Alternative	A	B	C	D	Points (Individual)	Points (Team)
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
				Total		

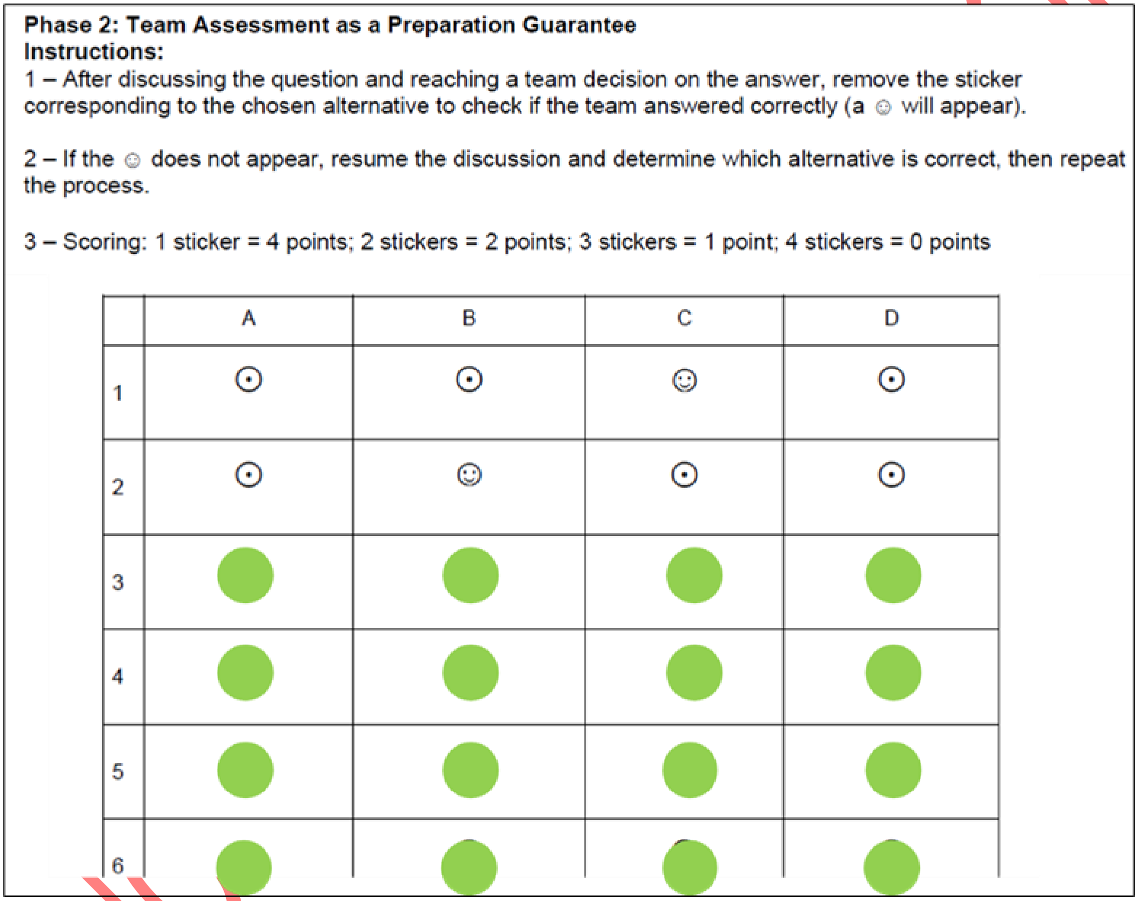
Figure 1. Answer Sheet for the Individual and Group Readiness Assurance Stage

In the individual test, students must allocate 4 points among the answer choices to indicate their confidence level in their selection. They may assign all 4 points to a single option if they know the correct answer. If uncertain between two choices, they can distribute the points equally (2 points each) or assign them proportionally, giving 3 points to the most likely option and 1 point to the other. If uncertain between the three alternatives, the 4 points should be distributed accordingly, with the most probable answer receiving the highest share. Finally, if all options seem equally possible, the student should assign 1 point to each alternative.

The third stage consists of group discussions in which students review the same questions from the individual test, allowing each member to present and justify their answers. According to [19], this process fosters the development of key skills, such as communication, argumentation, and persuasion, while reinforcing the importance of prior preparation for the activity.

The correct answer is verified using a tool, illustrated in Figure 2, which consists of a card with answer choices covered by removable stickers. The group's score is determined by the number of attempts required to identify the correct answer, following these criteria:

- First attempt: If the group selects the correct answer on the first try, they receive the maximum score of 4 points.
- Second attempt: If the correct answer is found after removing two stickers, the group earns 2 points.
- Third attempt: If the group succeeds on the third attempt, they receive 1 point.
- Fourth attempt or more: The group earns no points if all stickers are removed to find the correct answer.



Phase 2: Team Assessment as a Preparation Guarantee
Instructions:
1 – After discussing the question and reaching a team decision on the answer, remove the sticker corresponding to the chosen alternative to check if the team answered correctly (a ☺ will appear).

2 – If the ☺ does not appear, resume the discussion and determine which alternative is correct, then repeat the process.

3 – Scoring: 1 sticker = 4 points; 2 stickers = 2 points; 3 stickers = 1 point; 4 stickers = 0 points

	A	B	C	D
1	⊙	⊙	☺	⊙
2	⊙	☺	⊙	⊙
3	●	●	●	●
4	●	●	●	●
5	●	●	●	●
6	●	●	●	●

Figure 2. Immediate feedback card made with a printed sheet ('happy face' = correct answer) and covered with circular stickers

The individual test can be evaluated by identifying the correct answer to each question. Subsequently, teams can submit appeals if they disagree with the designated correct answer. To justify its reasoning, each appeal must be supported by well-founded arguments, improvement suggestions, and relevant bibliographic references [20].

To clarify how the team-based activity differed from an individual baseline, the assessment was intentionally structured in two sequential phases. In the first phase, students completed the questionnaire individually, relying solely on their prior preparation and personal interpretation of the assigned material. This individual assessment serves as a baseline, reflecting how students typically approach the task in a traditional, non-collaborative setting. In the second phase, the same questions were revisited in structured team discussions, allowing students to compare reasoning, negotiate answers, and collectively justify their choices. This design enabled a direct comparison between individual and collaborative problem-solving approaches within the same learning context.

CASE STUDY

This study was conducted with a class from the Graduate Program in Technology at the Universidade Estadual de Campinas (Unicamp), affiliated with the engineering courses of the School of Technology in Limeira, Brazil. The program aims to disseminate knowledge in technological fields and foster an interdisciplinary approach to education and research.

The course "Topics in Technology for the Environment I: Green Infrastructure and Spatial Data Tools" was selected for the TBL application and belongs to the environmental studies branch. Its syllabus covers: definitions, typologies, and scales of green infrastructure; environmental services and ecosystem services provided by these infrastructures; an introduction to geoprocessing and Geographic Information Systems (GIS); spatial data analysis in GIS environments; and case studies on implementing green infrastructure in urban areas. Two professors teach the course, and the TBL methodology was applied by a PhD student whose research focuses on GI.

The course was offered during the first academic semester of 2024 and included master's and PhD students with diverse educational backgrounds. TBL application was scheduled for the midpoint of the course, ensuring students had already developed a basic understanding of the key concepts.

The article "Green Infrastructure: A Systemic Approach of Urban-Rural Integration" [21] was selected to identify general guidelines for implementing urban GI to maximize its social and environmental benefits. Based on a literature review of the relevant concepts, the study examines the plan developed for Barcelona, which is considered an exemplary case of this emerging paradigm [21]. The material was selected for its comprehensive coverage of fundamental concepts related to the topic and for its application of a case study that can be replicated across different contexts.

The class consisted of ten students with diverse academic backgrounds, including architecture, environmental engineering, civil engineering, and law. To implement TBL, students were randomly divided into two groups of five members each. One week before the activity, they were informed that an active learning methodology would be used, but no specific details about its operation were provided. During this time, they were instructed to read the selected article in preparation for the activity.

At the beginning of the class, the PhD student responsible for the activity introduced himself to the group and explained the first stage of the process. Students had 45 minutes to complete a 10-question multiple-choice questionnaire individually, with each question containing four answer choices, each assigned a weight of 0 to 4 according to the method's principles.

Next, teams were randomly formed using the official class attendance list, with students divided into even- and odd-numbered groups. For another 45 minutes, the groups discussed their answers and collaborated to determine the correct alternatives. Finally, an additional 20-minute period was allocated for appeals, allowing teams to challenge and respond to key responses when disagreements arose.

The final implementation stage involved providing students with access to a "Class Evaluation Form (CEF)" via QR Code. This instrument was initially developed by [22] and later adapted by [23], as shown in Table 1.

Table 1. Comparison between theory and experiment

Q1. My state of mind when I arrived for class today was:									
1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
Q2. During the class, I would say I felt:									
1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
Q3. The topic covered in today's class, in terms of relevance to me, was:									
1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
Q4. Considering my effort, my assessment of my performance in class was:									
1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
Q5. The outcome I achieved in today's class, in terms of learning, was:									
1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
Q6. In my opinion, the professor's role in my learning was:									
1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
Q7. The class's contribution to my personal and professional development was:									
1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0

Students' answers to the CEF in each pedagogical intervention enables a comparative analysis of different lessons within the same course and an evaluation of student perceptions across various engineering disciplines and fields. This process helps identify strengths and challenges in implementing active learning methodologies, contributing to the continuous improvement of educational practices.

Learning Outcomes Assessment

Learning outcomes were operationalised through a structured two-phase assessment using the same evaluative instrument. It consisted of a 10-question multiple-choice questionnaire based on the text "Green Infrastructure: A Systemic Approach of Urban-Rural Integration" [21]. Each question presented four alternative answers, with only one correct option.

In Phase 1 (individual assessment), students completed the questionnaire independently, without discussion, serving as a baseline measure of individual comprehension. In Phase 2 (team-based assessment), students revisited the same questionnaire in structured teams, engaging in discussion and collective decision-making before submitting a unified group response. Each correct answer was worth 4 points, for a maximum possible score of 10. Scores were converted into percentages to allow comparison between individual and team performance.

To evaluate whether collaborative discussion significantly improved learning outcomes, a two-tailed paired t-test was used at $\alpha = 0.05$ to compare individual and team scores within the same cohort. In addition to quantitative performance measures, qualitative data were collected using the Class Evaluation Form (CEF), which employed a 10-point Likert-type scale to assess students' perceptions of engagement, understanding of Green Infrastructure concepts, and collaborative dynamics. Descriptive statistics (mean and standard deviation) were calculated for each item.

Quantitative and qualitative indicators were analysed independently without weighting, as they were designed to capture complementary dimensions of learning performance (objective achievement) and learning perception (subjective experience). Explicit description of the evaluation instrument, scoring procedure, and statistical analysis enhances methodological transparency and enables replication in similar graduate-level sustainability-oriented engineering contexts.

RESULTS AND DISCUSSION

Learning outcomes were assessed using a combination of quantitative and qualitative indicators, including individual and team questionnaire scores, statistical comparison of performance, and student self-assessment through the CEF. Results were divided into two parts: the first corresponds to the questionnaire scores, whereas the second refers to the student's self-assessment using the CEF. Table 2 presents the mean scores for the two phases of the TBL process, indicating that the average student scores were significantly higher in the group evaluation than in the individual assessment. Additionally, variability analysis shows that the standard deviation of individual scores (4.93) is higher than that of team scores (4.13), suggesting a more homogeneous distribution of learning among participants.

Table 2. Average student scores

Format	Number of correct answers
Individual	20.0 ± 4.93^{a}
Team	32.5 ± 4.13^{b}

*Mean value ± standard deviation. Values followed by different letters in the column differ statistically according to t-test ($p < 0.05$).

In total, ten students completed both assessment phases. Mean individual score was 20.0 ± 4.93, corresponding to 50% of the maximum possible score (40 points). After a structured team discussion, the mean team score increased to 32.5 ± 4.13, corresponding to 65% of the maximum score. A two-tailed paired t-test revealed that the difference between individual and team performance was statistically significant ($t = -5.4211$, $p = 0.0004$, $\alpha = 0.05$), indicating that collaborative discussion contributed to measurable improvement in learning outcomes.

The fact that TBL assessment emphasises team-based learning and fosters student discussion is a key factor in meaningful learning, as evinced by the significantly lower number of correct answers in the questionnaire when completed individually compared to when completed in teams. Moreover, results showed that the highest individual performance (27.0) was exceeded by both teams' performances (29.0 and 36.0). These findings highlight the importance of peer learning, as the TBL methodology aligns with the 'peer-to-peer' teaching approach which, according to [24], promotes the development of communication and interpersonal skills, responsibility, self-confidence, and student collaboration.

On average, students improved their scores by 12.5 points after team discussion, representing a relative increase of 62.5%. This gain suggests that peer interaction and collective reasoning contributed to deeper conceptual understanding of GI topics.

Out-of-class preparation and student engagement in constructing knowledge through the TBL methodology highlight learners' active role in their learning process. According to [25], student protagonism extends beyond classroom participation, playing a key role in knowledge formation and consolidation. By fostering this autonomy, TBL contributes to a comprehensive education, enabling students to develop intellectual independence and reinterpret theoretical content meaningfully.

As an active learning methodology, TBL promotes meaningful learning in which students play a central role in the educational process. For this approach to be practical, individual preparation is essential, including the assigned reading and prior research, which are key steps for the strategy's success [26].

CEF application provided valuable insights into students' perceptions regarding their learning experience, engagement, and the overall TBL effectiveness. The results, summarised in Table 3, indicate a positive evaluation of the TBL approach, with high average scores across all questions and relatively low variability in most responses.

Table 3. Average student responses related to the CEF

Question	Average Responses
Q1 (state of mind)	7.0 ± 3.1
Q2 (feeling during class)	8.9 ± 2.6
Q3 (relevance of the topic)	9.4 ± 0.8
Q4 (personal effort)	8.6 ± 1.3
Q5 (learning outcome)	8.2 ± 1.5
Q6 (instructor's role)	9.6 ± 0.8
Q7 (class contribution)	9.8 ± 0.6

Upon arriving in class (Q1: 7.0 ± 3.1), the student's state of mind showed the highest variability, suggesting that initial expectations and mood differed significantly among participants. This may indicate that some students arrive motivated and prepared, while others may have felt uncertain about the methodology or the topic. However, after participating in the session, their self-reported experience during class (Q2: 8.9 ± 2.6) showed a considerable increase with reduced variability, indicating that the session positively influenced students' engagement and comfort in the learning environment.

The topic's perceived relevance (Q3: 9.4 ± 0.8) received one of the highest ratings, with a low standard deviation, indicating strong consensus among students on the importance of GI as an educational subject. Similarly, the effort students perceived in their participation (Q4: 8.6 ± 1.3) was also high, reflecting active engagement in the methodology. The slightly higher variability in this response suggests that while most students felt actively involved, some may have encountered challenges in fully participating.

The learning outcome assessment (Q5: 8.2 ± 1.5) indicates that students generally felt they had learned effectively, though there was some individual variation that could be attributed to differences in prior knowledge, engagement levels, or learning preferences. The relatively low standard deviation of this response indicates that the TBL session consistently contributed to student learning.

The instructor's role (Q6: 9.6 ± 0.8) was highly rated, reflecting strong facilitation, clear instruction, and practical guidance throughout the session. This result aligns with the existing literature, which emphasises instructor engagement in active learning methodologies. Additionally, the class's contribution to personal and professional development (Q7: 9.8 ± 0.6) received the highest rating with the lowest variability, reinforcing that the team-based nature of the activity fostered collaboration, knowledge exchange, and an enriched learning environment.

These findings indicate that the TBL methodology was highly effective in engaging students, reinforcing key concepts, and creating an interactive learning environment. The relatively low standard deviations in most responses suggest a consistent learning experience among participants. Increased engagement and perceived learning outcomes further highlight the effectiveness of active learning methodologies in engineering education, mainly when applied to interdisciplinary topics such as GI.

The results also emphasize the instructor's key role in facilitating learning and guiding discussions, as well as the importance of peer interaction in enhancing students' understanding. Future implementations of TBL in similar contexts could further explore additional preparatory strategies to minimize variability in initial engagement levels (Q1) and ensure even more consistent learning experiences across participants.

Qualitative feedback collected through the CEF also indicated an evolution in students' perceptions of collaborative learning. Several students reported that while individual work initially felt more comfortable, team discussions helped them reconsider assumptions, clarify misunderstandings, and build confidence in applying GI concepts. This transition from individual reasoning to collective problem-solving was frequently highlighted as a key learning experience.

Challenges in Team-Based Work

Despite the overall positive outcomes of the TBL activity, students also faced challenges common to collaborative learning environments. Some participants reported initial difficulties with task delegation and balancing individual contributions within teams. Differences in academic background and prior familiarity with GI concepts occasionally led to uneven participation during early discussions. However, as the activity progressed, the instructor's guided facilitation and structured discussion phases helped mitigate these challenges, fostering more equitable engagement and shared responsibility among team members.

CONCLUSION

Beyond confirming TBL effectiveness, this study contributes novel insights by explicitly showing how collaborative assessment enhances the understanding of complex, interdisciplinary topics such as Green Infrastructure. By comparing individual and team-based performance in the same activity and examining students' perceptions of collaboration challenges and benefits, the study advances existing TBL research toward sustainability-oriented engineering education.

Our study evinces the effectiveness of TBL as an active methodology in a graduate-level engineering course, particularly in the context of GI education. Results showed that collaborative learning significantly improved student performance, as evinced by team assessment scores higher than individual assessment scores. Additionally, the TBL approach contributed to a more homogeneous learning experience, reducing participant variability and reinforcing the importance of peer interaction.

The CEF provided valuable insights into students' perceptions about the methodology, highlighting high engagement levels, perceived relevance of the topic, and the positive role of teamwork in knowledge construction. Instructor's facilitation and the collaborative classroom environment were also highly rated, further emphasizing the importance of structured guidance in active learning settings.

From a pedagogical perspective, the study reinforces TBL applicability in engineering education, particularly for interdisciplinary topics such as sustainable infrastructure. These findings suggest that peer-to-peer learning, structured discussions, and active engagement strategies enhance students' ability to analyse complex problems and apply theoretical knowledge in practical scenarios.

Future implementations of TBL in similar contexts could explore additional preparatory strategies to further minimize variability in student engagement and ensure a more consistent learning experience across participants. Moreover, further research is needed to assess long-term learning retention and its impact on professional skills development.

Thus, our study contributes novel insights into the application of active learning methodologies in engineering education, advancing discussions on innovative teaching strategies aligned with contemporary sustainability challenges. By bridging sustainability-oriented engineering content with structured collaborative assessment, it advances pedagogical innovation in engineering systems education and aligns educational practice with the interdisciplinary demands of sustainable development.

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NOMENCLATURE

Abbreviations

CEF	Class Evaluation Form
GI	Green Infrastructure
GIS	Geographic Information Systems
RAT	Readiness Assurance Test
SDGs	Sustainable Development Goals
TBL	Team-Based Learning
UNICAMP	Universidade Estadual de Campinas

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