

Article

Integrating Sustainability and Ethical Responsibility into Building Water Supply and Drainage Engineering Education: A CDIO-Based Curriculum Reform

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Abstract

Engineering education is increasingly expected to prepare graduates capable of addressing sustainability challenges, public safety concerns, and ethical responsibilities. However, in many civil and environmental engineering curricula, sustainability and ethics are still treated as supplementary topics rather than being systematically embedded in core technical courses. This study reports a sustainability-oriented curriculum reform implemented in a Building Water Supply and Drainage Engineering course, integrating Education for Sustainable Development (ESD) principles into CDIO-aligned project-based learning activities. A single-group pre–post quasi-experimental design was adopted with 100 undergraduate students. Quantitative data were collected using a competency-based questionnaire, and paired-sample *t*-tests, effect sizes, and 95% confidence intervals were applied to examine changes in students' self-reported competencies. Qualitative data were obtained from reflective learning reports and analyzed through thematic analysis. The results indicate statistically significant improvements in sustainability awareness, ethical and professional responsibility, human-centered design, and systems thinking, with large effect sizes. These findings provide context-specific descriptive evidence supporting the feasibility of embedding sustainability and ethical responsibility within discipline-specific technical engineering courses. Nevertheless, the absence of a control group and the reliance on self-reported measures limit causal interpretation. Future research is recommended to adopt comparative or longitudinal designs and incorporate more objective performance-based assessments.

Keywords: engineering education; education for sustainable development; CDIO; project-based learning; sustainability competencies; ethical responsibility; systems thinking



Academic Editor: David González-Gómez

Received: 22 January 2026

Revised: 8 February 2026

Accepted: 11 February 2026

Published: 13 February 2026

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1. Introduction

Engineering education worldwide is increasingly challenged to prepare graduates capable of addressing complex sustainability challenges, public safety concerns, and ethical responsibilities in contemporary society [1,2]. In response to global environmental pressures, resource constraints, and rising societal expectations, engineers are no longer expected to focus solely on technical problem-solving, but also to demonstrate professional responsibility, systems thinking, and sustainability awareness in their decision-making processes [3–7]. Consequently, higher education institutions are being urged to rethink traditional engineering curricula and to explore instructional approaches that integrate technical competence with value-oriented education [8,9].

Within this context, Engineering Education for Sustainable Development (EESD) has emerged as a key international agenda, emphasizing the systematic development of sustainability-related competencies in engineering programs [1,2,10]. Prior research has identified core sustainability competencies—such as systems thinking, ethical responsibility, and integrative problem-solving—as essential learning outcomes for future engineers [3,4,11,12]. These competency frameworks highlight the need to embed sustainability considerations within engineering education in a manner that connects technical knowledge with social, environmental, and ethical dimensions of professional practice.

To operationalize these goals, instructional frameworks such as Outcome-Based Education (OBE) and the CDIO (Conceive–Design–Implement–Operate) initiative have been widely adopted in engineering education [13–15]. These approaches emphasize constructive alignment among learning outcomes, teaching activities, and assessment methods, while promoting active and experiential learning through project-based and design-oriented pedagogies [8,9,16,17]. Empirical studies have shown that active learning and project-based learning can positively influence students' conceptual understanding and professional skill development in engineering contexts [8,9,18]. However, despite these advances, sustainability and ethics are still frequently addressed through stand-alone courses or supplementary modules, rather than being systematically embedded into core technical courses [16,19,20].

Building Water Supply and Drainage Engineering is a foundational course in civil and environmental engineering programs that occupies a critical position at the intersection of municipal infrastructure systems and building-scale water environments [5,6]. Engineering decisions in this field directly affect public health protection, user safety, and regulatory compliance, including drinking-water quality control, secondary contamination prevention, hot water scalding risks, and system reliability during daily building operation [5,7]. From both ethical and sustainability perspectives, design choices in building water systems carry immediate and tangible consequences for human well-being and environmental performance.

Despite these high-stakes implications, traditional instruction in Building Water Supply and Drainage Engineering has tended to emphasize technical calculations, design procedures, and code interpretation, with relatively limited attention to ethical responsibility, human-centered considerations, and system-level sustainability trade-offs [17,21]. As a result, students may acquire procedural design skills without fully understanding the broader social, environmental, and public health consequences of their engineering decisions [22,23]. While prior studies on EESD, CDIO-oriented curriculum reform, and project-based learning have reported positive outcomes in enhancing sustainability-related competencies [11,16,19,20,24], empirical evidence from discipline-specific technical courses—particularly those directly related to public health and building safety—remains limited.

To this end, the present study reports on a sustainability-oriented curriculum reform implemented in a core Building Water Supply and Drainage Engineering course at a single institution. The reform integrates sustainability awareness, ethical and professional responsibility, systems thinking, and human-centered design into project-based learning activities aligned with the CDIO framework, with the aim of supporting students' engagement in authentic engineering decision-making [13,15,17,18,20]. Rather than seeking to establish causal claims or broadly generalizable conclusions, this study provides context-specific empirical evidence from a single cohort to inform curriculum design and instructional practice in similar disciplinary settings.

Accordingly, this study is guided by the following research questions:

RQ1: To what extent does a sustainability-oriented curriculum reform influence students' sustainability awareness, ethical and professional responsibility, systems thinking, and human-centered design competencies in a Building Water Supply and Drainage Engineering course?

RQ2: How are these competencies manifested in students' project-based design performance and reflective learning outcomes?

2. Conceptual Framework and Course Design

The curriculum reform described in this study is guided by a conceptual framework designed to support the systematic integration of sustainability awareness, ethical and professional responsibility, systems thinking, and human-centered design into the technical instruction of Building Water Supply and Drainage Engineering (Table 1). Table 1 was developed by the authors to illustrate the constructive alignment between intended learning outcomes, teaching activities, and assessment evidence under the OBE and CDIO framework. The four learning-outcome dimensions were informed by widely used sustainability competency frameworks and engineering ethics education literature. As illustrated in Figure 1, the framework links intended learning outcomes, pedagogical strategies, and student learning processes in alignment with the principles of Outcome-Based Education (OBE) and the CDIO initiative [25–28].

Table 1. OBE-Aligned Mapping of Learning Outcomes, Teaching Activities, and Questionnaire Items.

Learning Outcome Dimension	Key Teaching Activities (Examples)	Assessment Evidence	Questionnaire Item Codes	Example Item Focus
Sustainability Awareness	Water-saving design; reclaimed water; energy-efficient hot water strategies	Pre-post questionnaire; design project	SA1–SA4	Awareness of water resource efficiency and environmental impacts
Ethical & Professional Responsibility	Failure case analysis; safety risk discussion; code-based reasoning	Pre-post questionnaire; reflection report	ER1–ER4	Professional duty, safety responsibility, and ethical reasoning
Systems Thinking	System-level trade-off evaluation; integrated design; multi-criteria decision-making	Pre-post questionnaire; project rubric	ST1–ST4	System interaction awareness and decision-making under constraints
Human-Centered Design	Public health scenarios; user-oriented design requirements; service-oriented thinking	Pre-post questionnaire; project rubric; reflection	HD1–HD4	User wellbeing, accessibility, and human-centered design considerations

Note: Item codes (SA/ER/ST/HD) were defined by the authors for reporting clarity; each dimension contained four Likert-scale items.

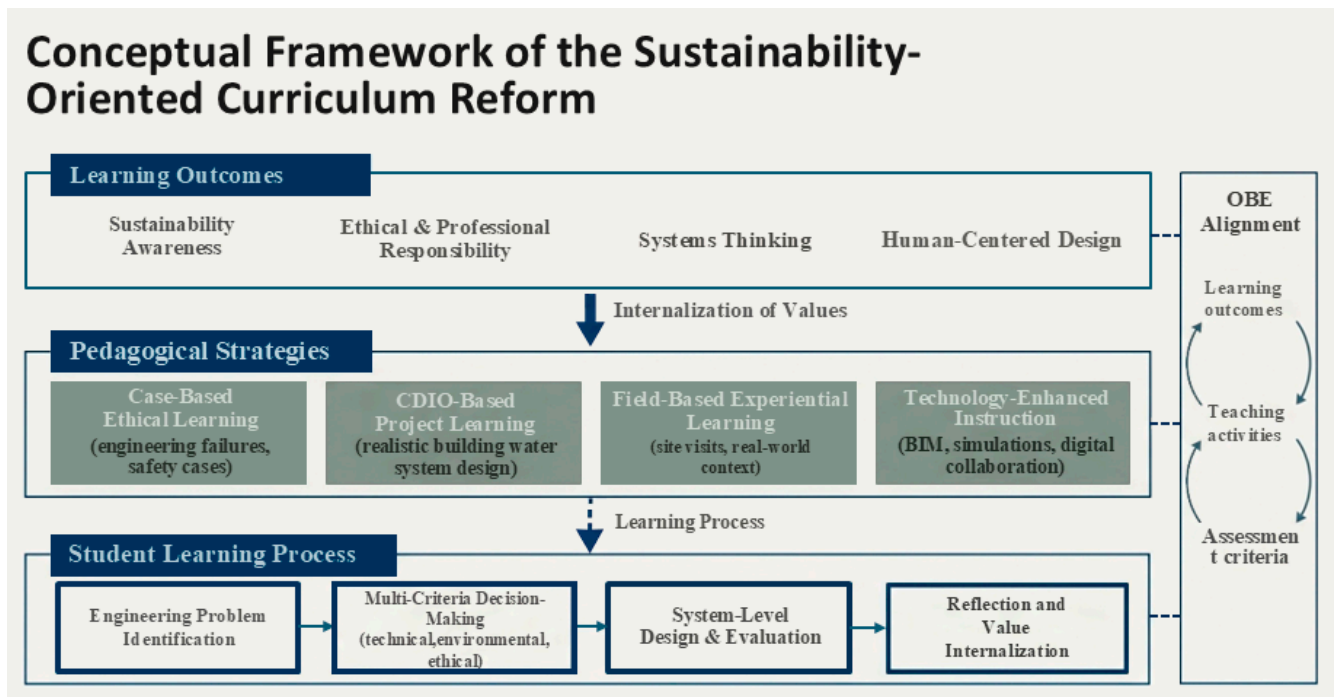


Figure 1. Conceptual framework of the sustainability-oriented curriculum reform. The framework illustrates how learning outcomes related to sustainability, ethics, systems thinking, and human-centered design are achieved through CDIO-based pedagogical strategies and value-integrated learning processes.

It should be emphasized that this framework is intended as a pedagogical and analytical organizing structure rather than a statistically validated or predictive theoretical model. Its primary purpose is to clarify the internal logic of the curriculum design and to provide a coherent structure for aligning learning objectives, instructional activities, and assessment methods, rather than to test causal mechanisms or generate generalizable theoretical claims [29,30].

Within the framework, sustainability-oriented learning outcomes are articulated across four dimensions: sustainability awareness, ethical and professional responsibility, systems thinking, and human-centered design. These outcomes reflect widely recognized competency domains in Engineering Education for Sustainable Development and are contextualized to the professional demands of building water supply and drainage engineering practice [21–23,25–28].

Pedagogical strategies were designed to embed these outcomes into core technical learning activities rather than treating them as supplementary content. Case-based ethical learning was employed to expose students to real-world engineering failures and safety incidents, encouraging reflection on professional responsibility and regulatory compliance. CDIO-based project learning engaged students in realistic building water system design tasks that required the consideration of technical performance, environmental impact, and user safety. Field-based experiential learning and technology-enhanced instruction further supported students' understanding of the operational and social contexts of engineering decision-making [13,14,29,30].

From a learning process perspective, the framework emphasizes a progression from engineering problem identification to multi-criteria decision-making, system-level design and evaluation, and reflective learning. This progression is intended to support students' gradual internalization of sustainability-related values through repeated engagement with authentic design challenges. This framework was used both to guide the instructional design and to structure the analysis of learning outcomes.

3. Methods

3.1. Research Design and Participants

A quasi-experimental pre–post design was adopted to examine the effects of the curriculum reform. A mixed-methods approach was employed to triangulate evidence from questionnaire data, project-based assessment, and student reflection reports [31].

Given the instructional evaluation purpose of the study and institutional constraints, no control or comparison group was included. Accordingly, the findings should be interpreted as descriptive evidence of learning changes associated with the curriculum reform rather than as causal effects.

Participants were 100 third-year undergraduate students majoring in Water Supply and Drainage Engineering at Yan'an University. The sample represented a full cohort of students enrolled in the course during the academic year. The intervention schedule is summarized in Table 2.

Table 2. Participants and Course Context.

Item	Description
Institution	Yan'an University
Program/Major	Water Supply and Drainage Engineering
Student level	Undergraduate (Year 3)
Sample size	n = 100 (full cohort)
Course title	Building Water Supply and Drainage Engineering
Course duration	16-week semester
Weekly contact hours	4 h/week
Total contact hours	64 h (theory) + 12 h (practice)
Teaching format	Lectures + case-based learning + project-based learning
Core project task	Building-level water supply and drainage system design with sustainability and ethics integration

3.2. Teaching Intervention

The sustainability-oriented curriculum reform was implemented over a 16-week semester and was aligned with the conceptual framework presented in Section 2. Sustainability awareness, ethical and professional responsibility, systems thinking, and human-centered design were integrated into core technical content through case-based ethical learning, CDIO-based project design tasks, field-based experiential activities, and technology-enhanced instruction [11,13,15,25,32,33]. The overall intervention structure and its alignment with the semester schedule are summarized in Figure 2.

Structure of the CDIO-based teaching intervention aligned with the 16-week course schedule.

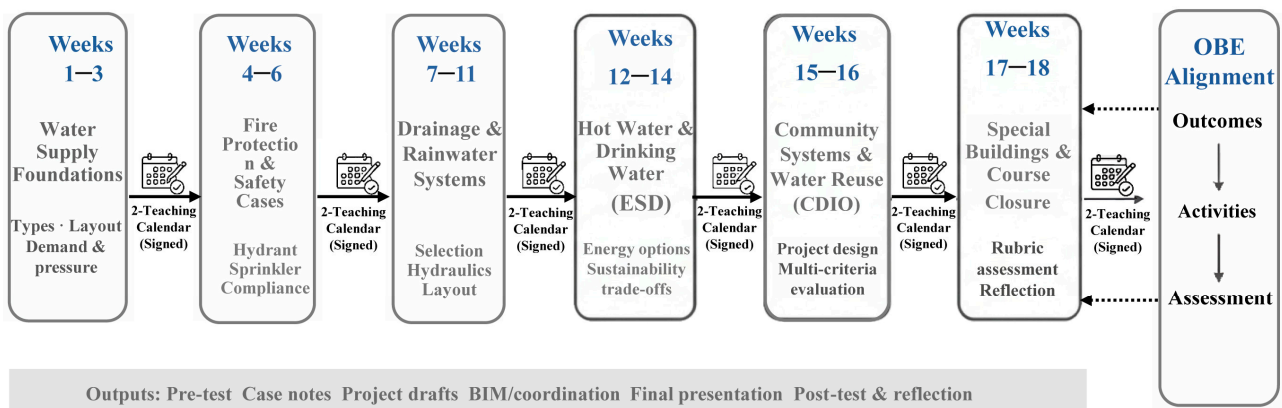


Figure 2. Structure of the CDIO-based teaching intervention aligned with the 16-week course schedule.

3.3. Data Collection Instruments

Student learning outcomes were assessed using a self-report questionnaire administered at the beginning (pre-test) and end (post-test) of the course [30]. The questionnaire consisted of items measuring four competency dimensions: sustainability awareness, ethical and professional responsibility, systems thinking, and human-centered design. Responses were recorded using a five-point Likert scale ranging from 1 (“strongly disagree”) to 5 (“strongly agree”). The full English version of the questionnaire is provided in Supplementary Table S1.

The questionnaire items were developed based on established sustainability competence frameworks in engineering education and were adapted to the context of Building Water Supply and Drainage Engineering. Prior to implementation, the items were reviewed by instructors with expertise in engineering education and professional practice to ensure content relevance and clarity [15,23,24].

Given the exploratory and formative purpose of the study, construct validity was addressed through theoretical alignment and expert review rather than through exploratory or confirmatory factor analysis.

Internal consistency reliability of the questionnaire was evaluated using Cronbach’s alpha, with coefficients ranging from 0.82 to 0.91 across the four competency dimensions, indicating good to excellent reliability [32]. Reliability was assessed for the overall dataset rather than separately for pre-test and post-test measurements, which is acknowledged as a methodological limitation.

In addition to questionnaire data, students completed a project-based design assignment in teams of four, resulting in a total of 25 design projects. A rubric was used to assess project performance across five dimensions: technical accuracy, sustainability performance, ethical and safety responsibility, human-centered design, and systems thinking.

To enhance scoring consistency, instructors jointly discussed the rubric criteria and assessed a subset of projects collaboratively to reach consensus prior to full evaluation. Final scores were determined through instructor agreement rather than independent scoring. The complete project-based assessment rubric is available in Supplementary Table S2. Students also submitted brief reflective reports describing their learning experiences related to sustainability, ethics, and engineering decision-making.

3.4. Data Analysis and Ethical Considerations

The paired-sample *t*-test assumes approximate normality of difference scores. Given the sample size ($n = 100$), the test was considered robust to moderate deviations from normality. However, potential testing and maturation effects inherent in pre–post designs are acknowledged as alternative explanations for the observed changes.

Quantitative data were analyzed using descriptive statistics (mean and standard deviation) and paired-sample *t*-tests to compare students' pre-test and post-test scores across the four learning outcome dimensions. Paired-sample *t*-tests were performed based on student-level matched pre–post responses. Statistical significance was determined at $p < 0.05$. In addition, Cohen's *d* was calculated to evaluate the practical magnitude of the observed changes. While the paired-sample *t*-test examines whether the pre–post differences are statistically significant, Cohen's *d* indicates the educationally meaningful effect size of the intervention [12,32].

In addition to *p*-values and effect sizes, 95% confidence intervals (95% CI) for the mean differences were calculated to quantify the precision of the estimated changes. The paired-sample *t*-test assumes that the difference scores are approximately normally distributed; however, given the relatively large sample size ($n = 100$), the test is generally robust against moderate violations of this assumption.

4. Results and Discussion

4.1. Changes in Self-Reported Learning Outcomes

Descriptive statistics and paired-sample *t*-test results for students' self-reported learning outcomes are presented in Table 3 and Figure 3. Across all four competency dimensions—sustainability awareness, ethical and professional responsibility, systems thinking, and human-centered design—post-test mean scores were higher than pre-test mean scores. Paired-sample *t*-test results indicated that the differences between pre-test and post-test scores were statistically significant for all four dimensions ($p < 0.001$), with effect sizes ranging from moderate to large. The specific results are as follows.

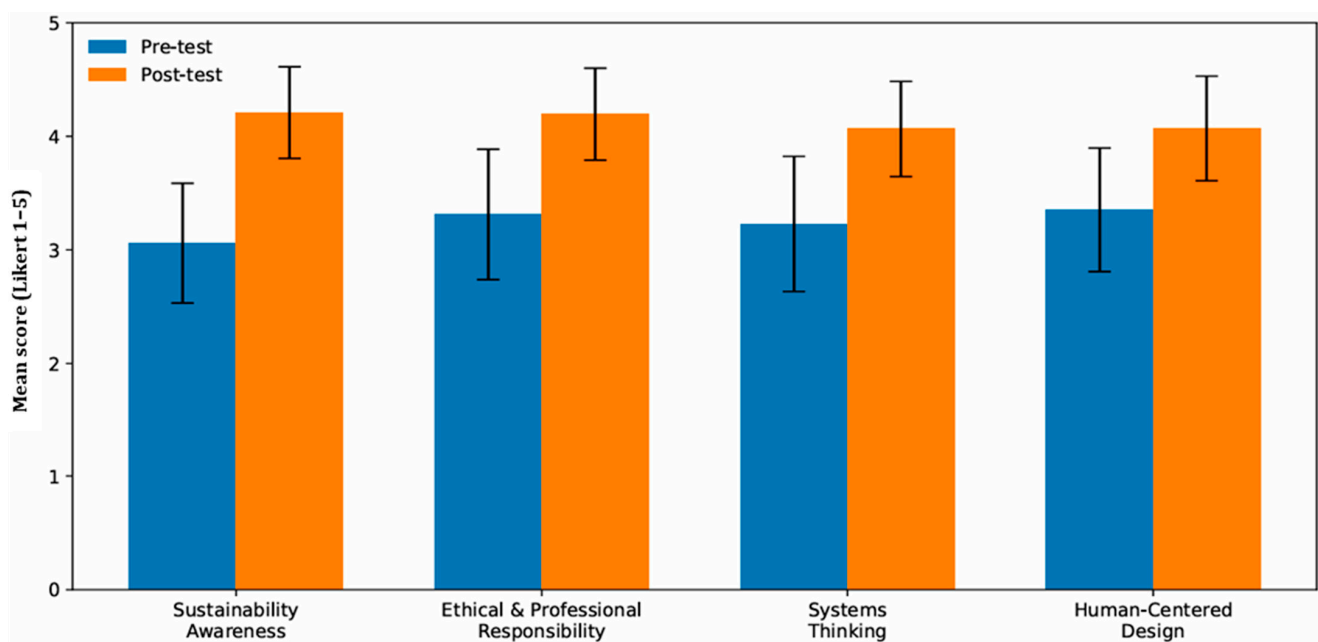


Figure 3. Pre–post comparison of learning outcomes ($n = 100$).

Table 3. Pre–Post Comparison of Sustainability-Oriented Learning Outcomes (n = 100).

Dimension	Pre-Test Mean $\pm$ SD	Post-Test Mean $\pm$ SD	t	p	95% CI of Difference	Cohen's d	Effect Level
Sustainability Awareness	3.06 $\pm$ 0.53	4.21 $\pm$ 0.40	16.46	<0.001	[1.01, 1.29]	1.65	Large
Ethical & Professional Responsibility	3.31 $\pm$ 0.57	4.20 $\pm$ 0.40	12.65	<0.001	[0.75, 1.03]	1.26	Large
Systems Thinking	3.23 $\pm$ 0.60	4.06 $\pm$ 0.42	11.02	<0.001	[0.68, 0.98]	1.10	Large
Human-Centered Design	3.35 $\pm$ 0.54	4.07 $\pm$ 0.46	9.55	<0.001	[0.57, 0.87]	0.95	Large

Note: Effect size levels follow common interpretation thresholds (Cohen's d: 0.2 = small, 0.5 = moderate, 0.8 = large). Mean difference = post-test – pre-test; CI = confidence interval.

Students' self-reported sustainability awareness showed a substantial increase following the course intervention. As presented in Table 3, the mean score rose from 3.06 (SD = 0.53) in the pre-test to 4.21 (SD = 0.40) in the post-test. The paired-sample *t*-test indicated that this difference was statistically significant ($t = 16.46$, $p < 0.001$). The magnitude of the change was large, with a Cohen's *d* value of 1.65, indicating a strong improvement in students' perceived sustainability awareness over the course duration.

A significant improvement was also observed in students' perceptions of **ethical and professional responsibility**, with the pre-test mean score of 3.31 (SD = 0.57) increasing to 4.20 (SD = 0.40) in the post-test. This difference was statistically significant ($t = 12.65$, $p < 0.001$). The effect size was large (Cohen's *d* = 1.26), suggesting a notable enhancement in students' awareness of ethical considerations and professional responsibilities in engineering practice.

Students' systems thinking competencies demonstrated marked gains after the instructional intervention. The mean score increased from 3.23 (SD = 0.60) in the pre-test to 4.06 (SD = 0.42) in the post-test. The paired-sample *t*-test confirmed that this change was statistically significant ($t = 11.02$, $p < 0.001$). The corresponding effect size was large (Cohen's *d* = 1.10), indicating a substantial improvement in students' perceived ability to consider system-level interactions and constraints in engineering decision-making.

Improvements were likewise identified in **human-centered design competencies**. The pre-test mean score of 3.35 (SD = 0.54) increased to 4.07 (SD = 0.46) in the post-test. This difference was statistically significant ($t = 9.55$, $p < 0.001$), with a large effect size (Cohen's *d* = 0.95). These results indicate a meaningful enhancement in students' self-reported consideration of user needs and social factors in engineering design processes.

Overall, these results indicate consistent positive changes in students' self-reported sustainability-related competencies over the course duration. These findings are consistent with prior studies reporting positive associations between project-based or CDIO-oriented learning approaches and sustainability-related competency development in engineering education [9,15,24]. However, given the single-group pre–post design, the observed improvements should be interpreted as learning changes associated with the curriculum reform rather than as definitive causal effects. Alternative explanations, such as testing effects or maturation over the semester, cannot be ruled out.

Notably, the magnitude of change varied across competency dimensions, suggesting that some competencies may be more readily influenced through course-level instructional interventions than others. This pattern aligns with previous research indicating that sustainability awareness and ethical responsibility may be more immediately responsive to curricular emphasis, whereas systems thinking often requires longer-term and repeated exposure [3,4,26,33].

4.2. Project-Based Design Performance

Students' application of sustainability-related competencies was further examined through analysis of project-based design assignments. A total of 25 team projects (100 students, four students per team) were evaluated using the rubric described in Section 3.3. The distribution of project scores across five assessment dimensions is summarized in Table 4 and Figure 4. Rubric scoring was conducted through instructor consensus rather than independent double rating, which is consistent with common instructional rubric-based evaluation practices in engineering education [33]. Higher average scores were observed for technical accuracy and ethical and safety responsibility, while comparatively lower average scores were observed for systems thinking.

Table 4. Project-Based Rubric Assessment Results (25 teams; 100 students, four students per team).

Rubric Dimension	Mean $\pm$ SD	Excellent (%)	Good (%)	Pass (%)	Needs Improvement (%)
Technical Accuracy	80 $\pm$ 5	20	30	40	10
Sustainability Performance	78 $\pm$ 3	16	28	32	24
Ethical & Safety Responsibility	85 $\pm$ 2	30	30	30	10
Human-Centered Design	80 $\pm$ 3	12	28	40	20
Systems Thinking	78 $\pm$ 3	10	30	35	25

Note: Performance categories are mutually exclusive and based on a 100-point rubric scoring system.

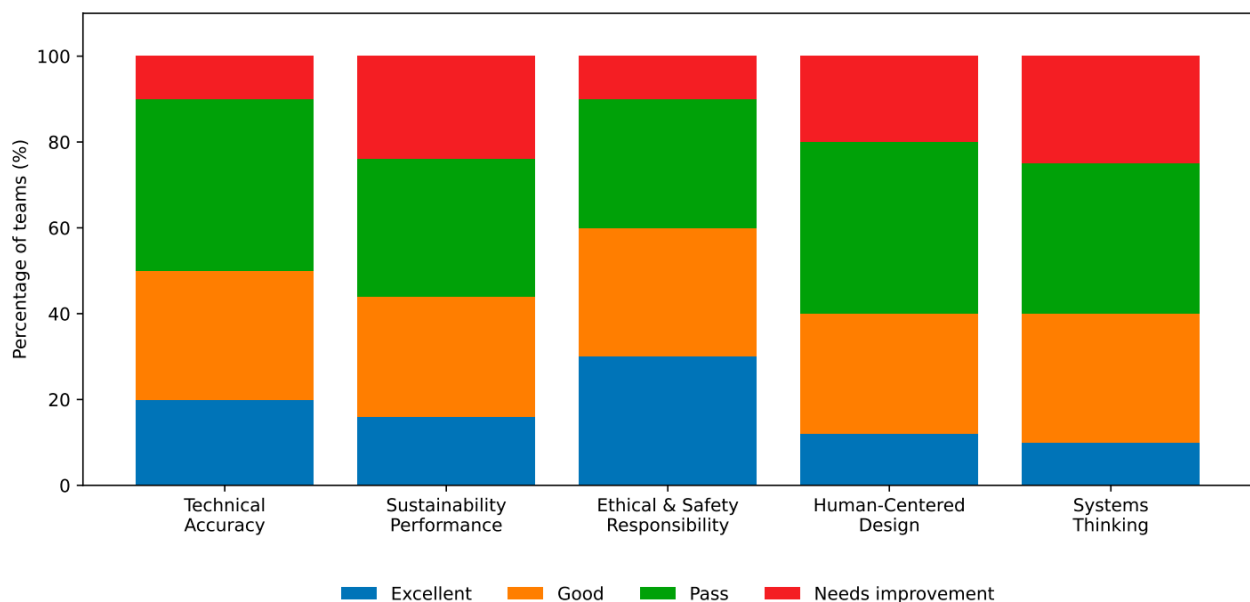


Figure 4. Distribution of project-based rubric performance levels (25 teams; 100 students, four students per team).

These results suggest that students were generally able to integrate ethical and safety considerations into technical design tasks, particularly when such considerations were explicitly embedded in project requirements and assessment criteria. This finding aligns with prior research showing that project-based learning and CDIO-oriented curriculum design can effectively enhance professional responsibility and sustainability-related competencies when authentic engineering problems are used as learning contexts [13,17,34]. In contrast,

the comparatively lower performance in systems thinking reflects the inherent complexity of system-level integration in building water supply and drainage design, which requires balancing technical performance, environmental impact, and user needs [25,28,35]. Moreover, since building water system design is closely linked to drinking-water safety and risk prevention, system-level decision-making must incorporate public health and water safety management considerations [5,7].

Importantly, the project-based assessment provides complementary evidence to self-reported questionnaire data by capturing observable design behaviors rather than perceptions alone, which has been emphasized as a valuable strategy for evaluating sustainability-related learning outcomes in engineering education [3,4,32]. Nevertheless, as project evaluation was conducted within an instructional context, the findings should be interpreted as indicative of students' demonstrated performance under guided conditions rather than as evidence of long-term professional competence.

4.3. Qualitative Insights from Student Reflection Reports

To complement the quantitative findings, qualitative data were collected from students' reflective learning reports submitted at the end of the course. A thematic analysis was conducted following the approach proposed by Braun and Clarke [32]. Those researchers independently reviewed all reflection texts, generated initial codes, and iteratively grouped them into broader themes through discussion until consensus was reached. This process aimed to enhance analytical transparency and reduce individual interpretation bias.

4.3.1. Enhanced Awareness of Engineering Ethics and Safety Responsibility

Many students explicitly reported a shift in their understanding of professional responsibility, particularly regarding safety and public health implications. One student noted: "In the past, I focused mainly on calculation accuracy and meeting technical standards. Through this course, I realized that design decisions in water supply systems directly affect user safety and public health, and ethical responsibility should guide every technical choice." (Student 18)

Such reflections indicate that embedding ethical considerations within technical design tasks encouraged students to move beyond procedural thinking and to recognize the moral dimensions of engineering practice.

4.3.2. Sustainability Awareness Embedded in Design Decision-Making

Students also demonstrated increased awareness of sustainability-related considerations when evaluating design alternatives. Rather than treating sustainability as an abstract concept, many students linked it directly to engineering trade-offs. For example, one student reflected: "When comparing different design schemes, I began to consider not only initial costs but also long-term energy consumption and water resource efficiency, which changed how I evaluated the 'best' solution." (Student 41)

This suggests that project-based learning tasks grounded in real-world building water systems helped students internalize sustainability principles as integral components of engineering decision-making.

4.3.3. Human-Centered Design and User-Oriented Perspectives

Another prominent theme concerned the importance of human-centered and socially responsible design. Several students emphasized the need to account for user comfort, vulnerable populations, and daily operational safety. One student stated: "Engineering design should not only meet codes, but also consider the needs of different users, such as the elderly and children, especially in terms of water temperature safety and accessibility." (Student 56)

These reflections highlight the role of authentic design contexts in fostering sensitivity to user needs and social responsibility within technically intensive courses.

4.3.4. Challenges in Developing Systems Thinking

While students acknowledged progress in integrating multiple considerations, some also expressed difficulties in achieving system-level reasoning. As one student commented: “It was challenging to balance technical feasibility, safety requirements, sustainability goals, and user needs at the same time, because these factors sometimes conflict with each other.” (Student 77)

This theme suggests that although the curriculum reform introduced system-oriented perspectives, developing robust systems thinking remains demanding and may require sustained reinforcement across multiple courses.

Overall, the qualitative findings support the quantitative results by illustrating how students interpreted and experienced the sustainability-oriented curriculum reform. However, it should be noted that these reflections are self-reported and may be influenced by social desirability bias, which warrants cautious interpretation.

4.4. Implications for Engineering Education for Sustainable Development

Taken together, the combined quantitative and qualitative results suggest that embedding sustainability and ethical considerations into a core technical course is associated with positive learning outcomes across multiple competency dimensions. From the perspective of Engineering Education for Sustainable Development (EESD), these findings provide empirical support for the feasibility of integrating sustainability-related competencies within discipline-specific engineering courses, rather than relying solely on stand-alone ethics or sustainability modules [1,2,11,35].

From a theoretical perspective, the results align with established sustainability competency frameworks that emphasize ethical responsibility, systems thinking, and sustainability awareness as core learning outcomes in engineering education [3,4,28]. Recent studies have similarly reported that students’ self-perceived ethical and social responsibility competencies can be strengthened through curriculum designs that explicitly connect technical problem-solving with broader societal and environmental considerations [10,36]. In this respect, the present study reinforces the view that value-oriented learning outcomes can be meaningfully addressed within technically intensive courses when pedagogical alignment is carefully designed.

From a practical perspective, the findings highlight the importance of aligning project tasks, assessment rubrics, and instructional activities with intended sustainability-related learning outcomes. In the context of Building Water Supply and Drainage Engineering, explicit attention to public health protection, user safety, and regulatory compliance appeared particularly effective in supporting students’ engagement with ethical and professional responsibility. Similar observations have been reported in sustainability-oriented engineering education studies, which emphasize that authentic design contexts and real-world constraints play a critical role in fostering students’ ethical awareness and social responsibility [33–36].

The effectiveness of the CDIO-based instructional approach observed in this study is also consistent with recent empirical research demonstrating that CDIO-oriented and project-based learning designs can support sustainability competency development even in highly technical engineering courses [35]. By embedding sustainability and ethical considerations directly into the design–implement–evaluate cycle, the curriculum reform allowed students to engage with sustainability not as abstract principles, but as integral elements of engineering decision-making.

An important observation from the results is that systems thinking exhibited comparatively smaller gains than other competency dimensions. This finding aligns with prior research suggesting that systems thinking represents a higher-order and integrative cognitive ability that often requires sustained and repeated exposure across multiple courses or learning experiences [26,28,34,36–38]. In the context of building water supply and drainage engineering, system-level reasoning involves balancing technical performance, public health protection, environmental impact, and user needs across interconnected subsystems [5–7]. Although the curriculum reform introduced system-oriented design considerations, the limited duration of a single course may have constrained the depth of systems thinking development. This result underscores the potential value of longitudinal or program-level instructional strategies for cultivating complex integrative competencies within EESD frameworks.

At a broader level, the findings of this study are consistent with global trends in engineering education that advocate for the systematic integration of sustainability into disciplinary curricula. Recent global reviews emphasize that embedding sustainability within core engineering courses—rather than treating it as peripheral content—is increasingly recognized as a key pathway toward achieving meaningful educational impact [35]. Curriculum-level reforms in diverse disciplinary contexts further highlight the importance of coherent course design and institutional support in sustaining sustainability-oriented educational change [39,40].

Overall, while the present study does not support causal claims due to its single-group pre–post design, it provides context-specific and discipline-based evidence that contributes to the growing body of EESD literature. By demonstrating how sustainability and ethical responsibility can be integrated into a core building services engineering course, this study offers practical insights for educators seeking to align technical instruction with sustainability-oriented learning objectives within engineering programs.

4.5. Limitations and Future Research Directions

Several limitations of this study should be acknowledged. First, the use of a single-group pre–post design without a control group limits internal validity and constrains causal interpretation. Second, the reliance on self-reported questionnaire data may introduce response bias. Third, the study was conducted within a single course at one institution, which limits the generalizability of the findings.

Future research could address these limitations by employing comparative or longitudinal designs, incorporating objective performance measures, and examining the persistence of learning outcomes beyond the immediate instructional context. Future studies could also incorporate objective measures such as exam-based design tasks or external evaluator scoring. Studies across multiple institutions or course sequences would further strengthen the evidence base for sustainability-oriented curriculum reform in engineering education.

5. Conclusions

This study investigated a sustainability-oriented curriculum reform implemented in a core Building Water Supply and Drainage Engineering course, with the aim of integrating sustainability and ethical responsibility into technical engineering education through CDIO-based project learning. Using a single-group pre–post quasi-experimental design, quantitative questionnaire data and qualitative reflective reports were collected from 100 undergraduate students.

The results indicated statistically significant improvements in students' self-reported sustainability awareness, ethical and professional responsibility, systems thinking, and

human-centered design competencies, all with large effect sizes. Evidence from project-based design performance and student reflections further suggested that students became more attentive to public health protection, safety requirements, and value-based decision-making when engaging in authentic technical design tasks.

From a theoretical perspective, the findings provide context-specific descriptive evidence supporting the feasibility of embedding Engineering Education for Sustainable Development (EESD) competencies within discipline-specific technical courses, rather than relying solely on stand-alone sustainability or ethics modules. From a practical perspective, the study highlights the importance of constructive alignment among intended learning outcomes, project tasks, teaching activities, and assessment rubrics in promoting sustainability-oriented learning within technical engineering curricula.

Nevertheless, the absence of a control group, the reliance on self-reported measures, and the short-term nature of the evaluation limit causal inference and may introduce potential response bias. Future research is therefore encouraged to adopt comparative or longitudinal designs, incorporate more objective performance-based indicators, and examine the sustainability of learning outcomes beyond the immediate course context.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18041933/s1>, Table S1: Sustainability-Oriented Learning Outcomes Questionnaire; Table S2: Project-Based Assessment Rubric (Team Evaluation).

Author Contributions: Conceptualization, T.H. and T.W.; methodology, T.H. and T.W.; teaching guidance, F.Z. and Y.H.; investigation, T.H., C.Y., L.L., X.W. and M.Y.; data curation, T.H. and M.Y.; formal analysis, T.H. and T.W.; writing—original draft preparation, T.H.; writing, review and editing, T.W., C.Y., F.Z. and Y.H.; visualization, T.H. and M.Y.; supervision, F.Z. and Y.H.; project administration, T.H.; resources, C.Y., L.L. and X.W.; funding acquisition, T.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Key R&D Program of Shaanxi Province, grant number 2025SF-YBXM-524, and the Yan'an University Teaching Reform Project, grant number YDJG23-50.

Institutional Review Board Statement: Ethical review and approval were waived for this study according to the relevant policies of Yan'an University and applicable regulations for educational research because Participation was voluntary, and informed consent was obtained from all participants; Data were collected anonymously or de-identified, and no personally identifiable information was included; Data were used solely for research purposes and stored securely by the research team; Findings are reported only in aggregated form.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

ABET	Accreditation Board for Engineering and Technology
CDIO	Conceive–Design–Implement–Operate
EESD	Engineering Education for Sustainable Development
ESD	Education for Sustainable Development
OBE	Outcome-Based Education
PBL	Project-Based Learning
BIM	Building Information Modeling
SDGs	Sustainable Development Goals

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