A Multidisciplinary Approach to Developing a Plastic Circularity Curriculum in Higher Education

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Abstract
Despite the growing emphasis on sustainability in higher education, formal and systematic instruction on plastic circularity remains limited in undergraduate and graduate programs. This project addresses that gap through the development and integration of an industry-aligned curriculum on plastics circularity across four departments at the University of South Alabama. The project team brings together expertise in plastics recycling and sustainability, polymer characterization, chemistry, systems engineering, and curriculum design. Collaboration with an industry advisory board ensures that course content remains relevant and responsive to current workforce and technological needs. The curriculum is guided by Bloom's Taxonomy to structure learning outcomes across cognitive levels and incorporates an experiential learning model to design course activities that promote hands-on, interdisciplinary engagement. A pilot course co-taught by five instructors demonstrated the feasibility and benefits of multidisciplinary teaching, with feedback from students and faculty highlighting increased understanding of circular systems and real-world applications. Through ongoing refinement and implementation, this initiative seeks to enhance educational pathways in sustainability, manufacturing, and systems thinking, thereby preparing a skilled workforce and contributing to the advancement of a circular economy for domestic plastics industries.
Keywords: Plastic circularity, curriculum development, multidisciplinary, sustainability, circular economy

1. Introduction

Plastics have become a critical part of the modern global economy, indispensable across everyday sectors like packaging, construction, transportation, agriculture, consumer goods, and healthcare [1]-[3], which is mostly due to their versatility, durability, lightweight properties, and low production cost. In fact, the only components or parts that are not made of plastic these days are those whose specific functions or safety standards cannot be achieved using plastic materials. The need for plastics has fueled an extraordinary rise in global production output from 1.5 million tons in 1950 to around 370 million tons in 2019, and demand is predicted to double by 2036 and possibly quadruple by 2050 [1], [4]. This rapid growth of plastic production has been accompanied by severe inefficiencies and failures in plastic waste management, largely due to the dominance of the linear "take–make–dispose" economic model of plastic production and usage [5]. Most conventional plastics are produced from fossil fuels, engineered for durability, and resistant to degradation, resulting in persistence in landfills and natural ecosystems for centuries. Despite decades of recycling advocacy, only about 9% of all plastics ever produced have been recycled, while an estimated 12% have been incinerated, and nearly 79% have accumulated in landfills or leaked into the environment [6], [7]. This contributes to pervasive pollution, ecosystem degradation, and growing human health concerns associated with microplastics and other environmental impacts [8]-[11], necessitating systemic transformation in how plastics are designed, used, recovered, and valued.

In recent years, global institutions, policymakers, industries, and academic communities have increasingly advocated for a fundamental shift from the traditional linear model to a circular economy model. In a circular plastic economy model, plastics are designed for durability, reuse, and recyclability, enabling them to circulate within economic systems rather than becoming waste [5], [12], [13]. This model emphasizes strategies such as reducing plastic waste and pollution through product design, retaining resources and products in use, and regenerating and preserving natural systems [14], [15]. The vision is that plastics should never become waste but should re-enter the economy as valuable resources, thus achieving both environmental protection and economic efficiency. Transitioning from the linear to circular economic model requires coordinated interventions in material science, product design, policy frameworks, business models, waste management infrastructure, and consumer behavior, highlighting the complexity and interdependence of the circular model [1], [16].

Higher education institutions are uniquely positioned to accelerate this transition by cultivating the next generation of scientists, engineers, policymakers, and innovators capable of leading circularity initiatives. Since 2019, the academic literature describing circular economy and plastics circularity courses has grown rapidly [17], reflecting rising global interest and policy momentum, including the prioritization of plastics within the circular economy action plan and other initiatives worldwide. Higher education institutions increasingly serve as strategic agents in promoting restorative and regenerative economic models through curriculum innovation, campus operations, and applied research. Early initiatives in circular economy education have explored diverse applied projects. For example, research projects have included analyzing plastic waste in university dining systems and creating a system to reduce it [18], recovery of rare earth metals from small fluorescent lights and phosphors used in white light-emitting diodes [19], and testing compostable alternatives to single-use plastics [17], [20]. These examples illustrate growing academic engagement but also highlight the need for more structured, comprehensive educational approaches.

Education for circular economy requires more than traditional lecture-based instruction; it should be competency-driven and grounded in systems-oriented and experiential training. Circular economy learning frameworks emphasize life cycle thinking, systems thinking, and the integration of real-world, problem-based experiences [21]. Active learning methods that require applying theoretical concepts to real-world projects and integrating collaboration across academic fields are being emphasized, while learning approaches such as project-based learning, flipped classroom, and challenge-based learning, case-based learning, and serious games like “In the Loop”, have been adopted to provide experiential learning and stimulate holistic thinking [17], [21]-[24]. Additionally, specialized methodologies such as circular pathway, an eight-step approach for exploratory redesign of product value chains, have been adopted to guide students in applying circular strategies across multiple system levels [22]. These education models reflect the inherently interdisciplinary and applied nature of circular economy, requiring learners to synthesize scientific, technical, economic, policy, and social dimensions. However, despite these established best practices, many circular economy and plastics circularity programs still struggle to integrate them effectively.

As a result, substantial gaps and limitations persist in circular economy and plastics circularity education. Existing curricula sometimes emphasize isolated technical or environmental concepts while offering limited integration of interdisciplinary problem-solving and systems-level thinking essential for addressing real-world plastic flows [25]. Furthermore, digital technologies, such as material-tracking tools, data analytics, and smart waste systems, are also underutilized despite their growing importance in optimizing circular systems [25]. Additionally, many circular economy programs provide only a broad overview of sustainability and give limited attention to plastics-specific circularity, leaving students without polymer chemistry, materials behavior, and supply-chain knowledge necessary to understand plastic recycling challenges. Educational models also tend to prioritize supply-side processes while overlooking demand-side strategies such as reduction, reuse, repair, and high-value retention [21], [26]. Institutional constraints, including limited plastic circularity competency frameworks, lengthy curriculum approval processes, resource challenges, and a shortage of qualified instructors, further hinder curriculum development [21], [26]. Students additionally face restricted access to industrial data, limiting their ability to perform realistic analyses of circular supply chains [22], [27].

Addressing these gaps requires a multidisciplinary, technically grounded, and pedagogically structured approach. This paper presents a university-level plastics circularity curriculum designed to fill these needs through a Bloom's Taxonomy-based structure, integrating polymer and materials science, and experiential learning through laboratory modules and field visits. The curriculum offers a scalable model for higher education institutions seeking to strengthen plastics circularity education and prepare students for emerging roles in circular economy innovation.

2. Methods

2.1 Pedagogical Framework

The curriculum was developed using a structured pedagogical framework that integrates principles of plastic circularity with evidence-based educational strategies and emerging circular economy competency models. In particular, the instructional design was informed by global circular economy education frameworks proposed by the United Nations Educational, Scientific and Cultural Organization (UNESCO)'s Education for Sustainable Development (ESD) competencies [28] as well as insights from recent literature on circular economy education [21]-[25]. These models emphasize systems thinking, resource stewardship, interdisciplinary collaboration, and innovation, competencies that were deliberately embedded throughout the course. As illustrated in **Figure 1**, the framework positions plastic circularity within a closed-loop system, emphasizing continuous recycling, repurposing, and value retention to reduce dependence on virgin polymer production and minimize environmental impacts across the materials lifecycle. A multidisciplinary instructional team, including faculty in civil engineering, chemistry, materials science, and environmental systems, supported the design and implementation of the curriculum.

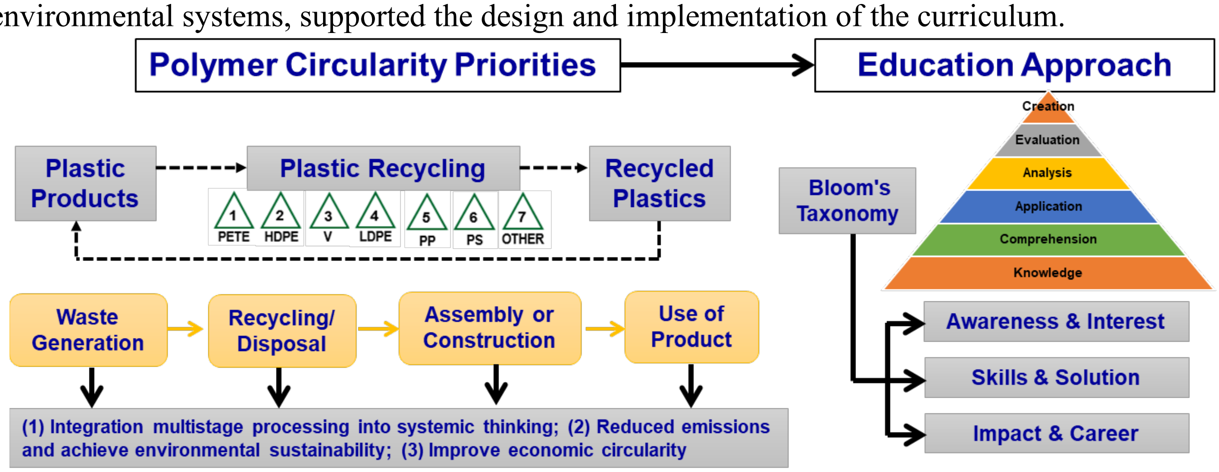


Figure 1. Framework to integrate polymer circularity and Bloom's taxonomy into curricula.

Bloom's Taxonomy, which is a hierarchical framework that categorizes cognitive skills, was integrated into the course design. This taxonomy comprises six cognitive domains: knowledge, comprehension, application, analysis, evaluation, and creation [29]. By embedding Bloom's Taxonomy into curriculum development and instructional activities, the course aims to enhance students' awareness, interest, and engagement with principles of plastic circularity. From a technical perspective, students are expected to acquire essential competencies in materials characterization, systems thinking, and innovative problem-solving, thereby preparing them for future roles in industry and research.

Experiential learning, a key feature across all circular economy frameworks [17], [23], [26], was intentionally integrated into the course to bridge the gap between theoretical understanding and practical application. Field trips to waste-management and recycling facilities provided opportunities for students to contextualize abstract concepts of material recovery, observe the physical realities of waste diversion, and engage directly with personnel to learn about the operational challenges, regulatory constraints, and technologies currently in use. These visits allowed students to examine the complexities of closing material loops from the perspective of practitioners who work at different stages of the value chain. Laboratory sessions served as controlled environments for experimentation and technical verification that enable students to test the feasibility and performance of secondary materials, such as recycled polymers, and evaluate their suitability for circular product design and resource optimization. Complementing these technical components, community-engaged activities encouraged collaboration and responsible action by exposing students to the social and behavioral dynamics that influence plastics consumption and reuse, areas often overlooked in purely technical curricula. This integrated experiential approach not only exposed students to real-world challenges but also positioned them to apply CE principles through observation, experimentation, and community engagement, which further strengthened their innovation literacy and systems-thinking abilities.

2.2 Course Design

The course was developed to equip students with a comprehensive understanding of plastic circularity by combining technical knowledge, systems thinking, and professional communication skills. The intended learning outcomes targeted conceptual knowledge, laboratory-based material evaluation, real-world waste-management awareness, innovation literacy, and the synthesis of real-world solutions aligned with circular economy principles. These outcomes supported the overall objective of preparing students to engage with emerging sustainability challenges across industry and research settings. The six learning outcomes developed for the course are presented in **Table 1**, reflecting expected progression from foundational knowledge acquisition to advanced application and solution development.

Table 1. Course Learning Outcomes

Learning Outcome	Description
1	Describe plastic circularity concepts and evaluate the environmental impacts of plastic waste.
2	Analyze polymer properties and performance using laboratory experiments and data analysis.
3	Explain waste management strategies and recycling technologies based on field observations.
4	Illustrate innovations in plastic circularity, including circular models, applications, and sustainable design principles.
5	Identify relevant standards, codes, and specifications, and communicate results through technical writing and presentations.
6	Apply multidisciplinary knowledge and systems thinking to propose and evaluate solutions to a real plastic circularity challenge

2.2.1 Course Modules and Key Topics

The course content was organized into seven interconnected modules as presented in **Table 2**. The modules are designed to build students' understanding of materials, systems, and circularity strategies in a logical progression.

Table 2. Course Modules, Key Topics, and Experiential Elements

Module	Focus Area	Key Topics Covered	Experiential Learning Component
I	Fundamentals	Plastic circularity concepts, terminology, industrial relevance, and environmental impacts	Field visit to county recycling center to observe sorting systems, contamination issues, and community-level recycling challenges; interaction with facility personnel regarding operational constraints and public behavior patterns
II & IV	Polymer and Plastics Fundamentals	Chemistry and synthesis, processing, chemical and physical characterization	Physical lab: Differential Scanning Calorimetry (DSC) and Fourier Transform Infrared Spectroscopy (FTIR) hands-on analysis to identify unknown plastics and examine material compatibility for recycling; Remote lab: ASTM D790 (Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials) flexural testing demonstration with real data interpretation; observation of failure characteristics and mechanical limitations of recycled materials
III	Plastic Waste Management	Waste sources and types, management challenges, regulatory frameworks, and current practices	Industrial field visit to KW Plastics, the world's largest plastics recycler, to examine large-scale processing, markets, sorting technologies, and performance expectations from industry

V	Recycling Techniques	Mechanical and chemical recycling, emerging recycling methods	Guest lecture and live Q&A with recycling industry specialist; exploration of technology maturity, cost barriers, and innovation pathways
VI	Designing for Circularity	Circular design principles, design strategies, and life cycle assessment	Phase 1: Investigation of real Gulf Coast plastic failure (seafood clamshell system); Phase 2: Redesign using circular strategies; Phase 3: Proposal of scalable commercialization/implementation model addressing stakeholders, infrastructure, production, and consumer behavior
VII	Innovations and Applications	State-of-the-art circularity practices, case studies, and repurposing waste plastics	Poster symposium with academia, industry, and community stakeholders; student engagement in professional communication, defense of design, and feedback integration

2.2.2 Course Assessment

Student performance was evaluated using a structured assessment approach that emphasized conceptual understanding, experiential engagement, and applied problem-solving. Homework reinforced the concepts introduced in each module, while field work allowed students to connect what they learned with real recycling and waste-management practices. The term project gave students the chance to explore a plastic circularity topic in depth, and the final presentation assessed their ability to communicate their findings clearly and professionally. The breakdown of assessment components is summarized in **Table 3**.

Table 3. Assessment Components

Assessment Component	**Weight**	**Description**
Homework	30%	Assigned after each module to reinforce concepts; required full solutions and timely submission.
Field Work	20%	Participation in field trips and submission of a formal report documenting observations and insights from site visits.
Term Project	30%	Independent project on a plastic circularity topic; undergraduate students produced a technical report, graduate students produced a journal-style manuscript.
Presentation	20%	Oral presentation of the term project to faculty, peers, and industry/community attendees, demonstrating analytical and communication skills.

2.3 Implementation of Course

The course was implemented in the Summer of 2025 with a total enrollment of 11 students. It followed a hybrid instructional model, with most of the lecture content delivered asynchronously through the Canvas platform and supported by a combination of physical and remote laboratory experiences as described in **Table 4**. The course was organized to progress from understanding foundational concepts, to understanding mechanistic and then systems-level application. Module I introduced students to core circular economy concepts and material flow principles, reinforced through a field visit to a local recycling center. Module II focused on polymer and plastics chemical fundamentals and included a hands-on laboratory experience in which students applied DSC and FTIR techniques to identify unknown recycled plastic samples. These early modules established the conceptual and analytical foundation required for subsequent technical and applied content.

Table 4. Schedule for the Pilot Plastic Circularity Course

Week	Dates	Topic (Led by Instructor)	Homework / Assessment Activities
1	6/4 to 6/8	Module I: Introduction and field trip to a local recycling center (Led by Instructor A)	After-class homework reinforcing terminology, material flow concepts, and CE fundamentals; reflection report based on recycling center visit
2	6/9 to 6/15	Module II: Polymer and plastics chemical fundamentals with lab (Led by Instructor B)	In-class quizzes to assess conceptual understanding; Pre-lab assignment; Post-lab data analysis; Laboratory report identifying recycled plastics types using DSC and FTIR
3	6/16 to 6/22	Module III: Plastic waste management and field trip to KW Plastics (Led by Instructor A)	After-lecture quiz assessing concepts and terminology; Field memo evaluating waste systems, infrastructure barriers, and policy challenges
4	6/23 to 6/29	Module IV: Polymer and plastics mechanistic fundamentals with lab (Led by Instructor C)	In-class quizzes linked to polymer chemistry; Virtual ASTM D790 (structural test) lab assignment, interpreting flexural performance and design implications
5	6/30 to 7/6	Module V: Recycling techniques and guest speaker (Led by Instructor D and A)	Homework analyzing the feasibility, cost considerations, and technical trade-offs of mechanical and chemical recycling
6	7/7 to 7/13	Module VI: Designing for circularity (Led by Instructor E)	Phase 1 report investigating Gulf Coast Sea food packaging failure and mapping system breakdowns; Phase 2 redesign proposal applying circular design principles; Phase 3 implementation strategy addressing scalability, stakeholder adoption, and infrastructure
7	7/14 to 7/20	Module VII: Innovations and Applications, guest speaker (Led by Instructor A)	-
8	7/21 to 7/27	Final Presentation/Symposium	Poster presentation defending the proposed solution to academic, industry, and community attendees
9	7/28 to 8/1	Final Project	Final Report

Progression towards the mid portion of the course emphasized plastic waste systems and material performance behavior. In Module III, students examined plastic waste management infrastructure and policy challenges through lectures and a field visit to an industrial recycling facility. Module IV then connected polymer chemistry to mechanical performance through a mechanistic perspective, using a remote ASTM D790 flexural test demonstration to help students interpret structural behavior and relate test outcomes to recycled material performance. Module V expanded this understanding by examining mechanical and chemical recycling techniques, with additional insight provided by a guest speaker and feasibility-focused homework assignments.

The latter portion of the course moved toward design, innovation, and real-world application. Module VI served as the central application component, structured as a three-phase design challenge addressing a real Gulf Coast seafood packaging system. Students first investigated system failures associated with seafood clamshell trays, then developed redesigned packaging concepts grounded in circular design principles, and finally proposed feasible implementation strategies addressing scalability, infrastructure, and stakeholder adoption. Module VII further broadened this perspective by exposing students to emerging innovations and applications through guest lectures.

The course concluded with a poster presentation symposium and a final written project in which students defended their proposed solutions before academic, industry, and community audiences. Throughout the term project in Module VI, students made structured use of an interactive AI-supported design tool embedded within the course. The tool functioned as a collaborative design partner by enabling iterative brainstorming, systems-level questioning, evaluation of alternative circular design pathways, and refinement of technical and implementation decisions, while preserving student ownership and accountability for the final deliverables.

To further enhance experiential learning and support competencies in systems thinking, stakeholder engagement, and real-world problem exploration, several field-based activities were incorporated into the program. First, a field trip to a local recycling center was conducted to deepen students' understanding of community-level plastic recycling practices and to observe how waste plastics are sorted and managed (**Figure 2a**). Second, students participated in a site visit with guidance from a local industry partner to install a novel plastic trash interceptor in a nearby creek, which encouraged them to consider innovative approaches to plastic waste collection (**Figure 2b**). Third, a visit to the world's largest plastic recycler provided students with valuable exposure to industrial-scale processing, operations, management practices, and professional roles in the recycling sector (**Figure 2c**). Finally, a poster presentation session was held with attendees from academia, industry, and the local community, supporting communication, collaboration, and civic engagement. Each student engaged with the audience and presented their ideas and proposed solutions related to plastic circularity (**Figure 2d**).

(a)

(b)

(c)

(d)

Figure 2. Experiential learning activities: (a) visit local recycling center; (b) visit a novel plastic waste interceptor on a creek by a local industry; (c) visit the largest plastic recycler, KW Plastics in Troy, AL; (d) Final poster presentation.

2.4 Course Assessment

As this is the first time to have multiple instructors for teaching one course, an independent course assessment was conducted to evaluate both instructional effectiveness and student learning outcomes. A mixed-methods approach was used, integrating pre-, mid-, and post-course student surveys administered through an online questionnaire, performance-based assessment data, and semi-structured interviews with both students and faculty. The surveys (**Appendix Table A1**) tracked changes in students' self-reported familiarity and understanding with core topics including plastic circularity, polymer behavior, recycling technologies, environmental impacts, and circular design using a five-point Likert scale, while open-ended questions allowed students to reflect on their learning experiences. Student performance was evaluated using data from quizzes, laboratory assignments, field reflections reports, and the design project, providing insight into conceptual understanding, technical proficiency, and systems-level problem-solving skills. Interviews with students and instructors offered additional perspective on course implementation, interdisciplinary coordination, and student engagement. Quantitative data were examined using descriptive statistics to identify learning trends over time, while qualitative responses were analyzed through thematic content analysis to capture recurring strengths, challenges, and opportunities for improving future offerings of the course.

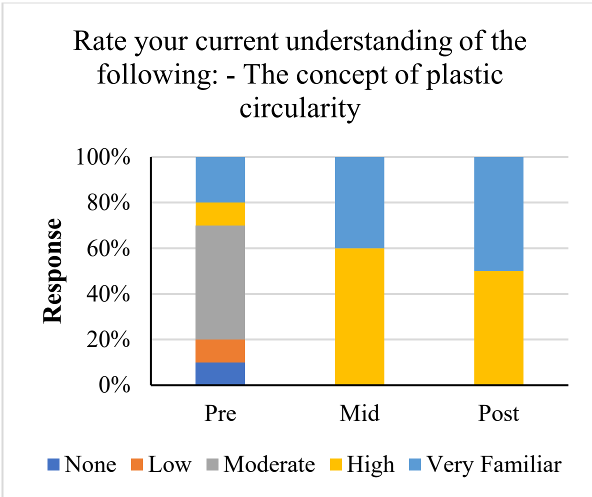
3. Results and Discussions

This section presents the findings from the course assessment and examines how effectively the Plastic Circularity course achieved its intended educational goals. The results address three central questions: whether the course improved students' understanding of plastic circularity and related technical concepts, how well the hybrid and interdisciplinary instructional model supported student learning, and how students and faculty perceived the strengths and limitations of the course design. Quantitative survey results and performance-based assessment data are first used to evaluate learning gains and mastery of course competencies, followed by qualitative insights from student and faculty feedback that help contextualize these outcomes and inform future course improvements.

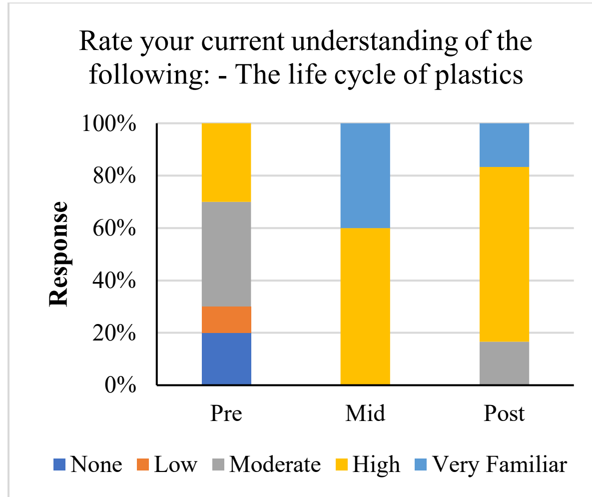
3.1 Quantitative Analysis

Pre- (N=10), mid- (N=5), and post-course (N=6) surveys were used to evaluate student learning, drawing participants from various background including; Civil Engineering (majority in both pre and post surveys), Systems Engineering, Environmental Toxicology, and Electrical Engineering, with 60% (6 of 10) of students reporting no prior coursework in sustainability, recycling, or materials science and only 40% (4 of 10) indicating previous exposure. This disciplinary composition remained consistent across the semester. The results, presented in **Figures 3(a)** to **3(f)**, show substantial improvements in students' understanding of plastic circularity and related technical competencies. At the beginning of the course, most students reported limited familiarity with core topics, particularly polymer behavior, recycling technologies, and circular design, where responses were heavily concentrated in the "None," "Low," or "Moderate" categories. By mid-semester, this distribution shifted drastically toward higher levels of familiarity, with a majority of students selecting "High" or "Very Familiar" across most topics. These improvements continued through the post-course assessment, indicating sustained growth as students progressed through subsequent modules. This pattern mirrors findings from a prior study involving larger undergraduate and postgraduate cohorts, which similarly reported low baseline familiarity with circular economy topics [26].

The most notable improvements were observed in technically intensive areas. For polymer properties and performance (**Figure 3e**), 60% (6 of 10) of students initially rated themselves as having "None" or "Low" familiarity; however, by the end of the course, all students rated themselves at least "Moderate," with 83% (5 of 6) selecting "High" or "Very Familiar." A similar pattern was observed for mechanical and chemical recycling techniques (**Figure 3c**), where early unfamiliarity gave way to strong end-of-semester confidence. These shifts align closely with the course's laboratory sequences, virtual testing activities, and recycling technology modules, suggesting that the hybrid instructional model was particularly effective for strengthening technical competencies. Circular design and sustainable solutions (**Figure 3f**) also showed one of the strongest gains, with the proportion of students reporting "High" or "Very Familiar" rising from 40% at the start to 100% in the final survey, mirroring the impact of the design-based learning phases and the real-world innovation task. Even in areas where prior knowledge was relatively high, such as the environmental impact of plastic waste (**Figure 3d**), the final ratings indicate deeper and more consistent understanding, with the entire class reaching "High" or "Very Familiar." This outcome reflects the impact of the multi-phase, real-world design challenge and supports prior findings [17], [21], [22] that CE learning outcomes improve most effectively when students engage in authentic, application-driven tasks that require systems-level reasoning and trade-off analysis.



(a)



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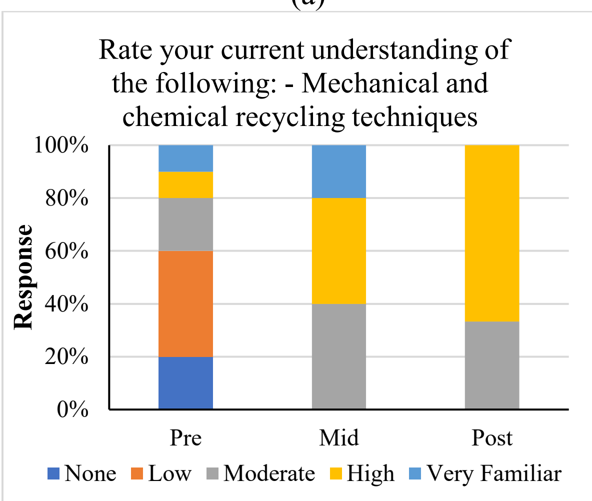

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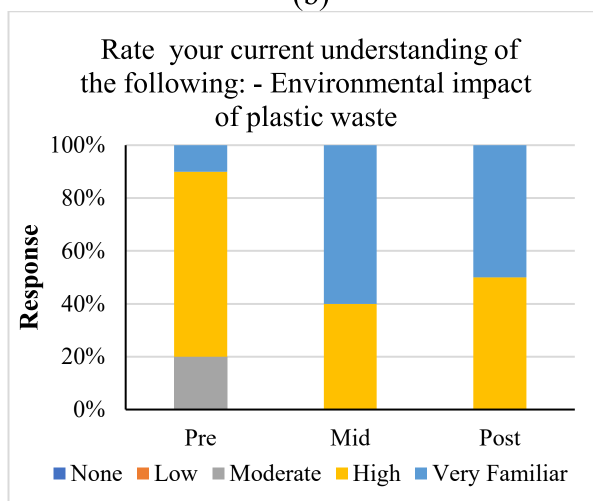

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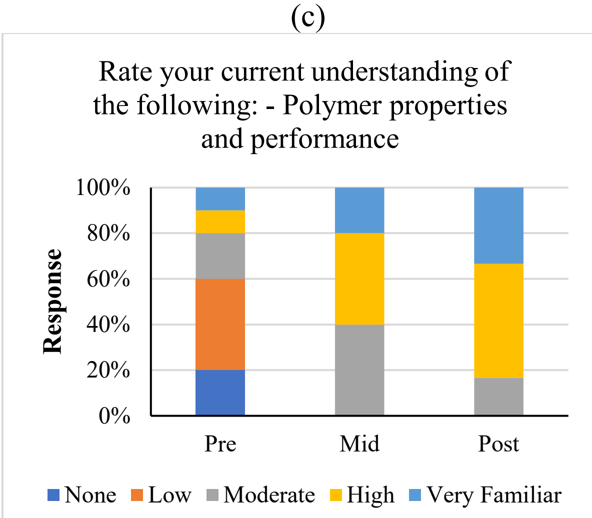

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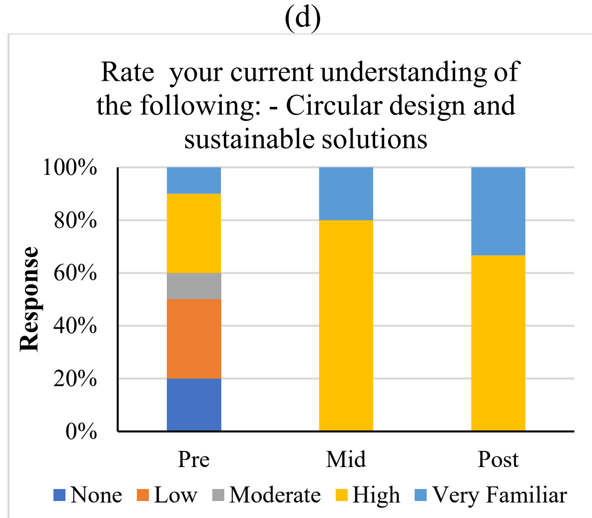

(f)

Figures 3. Survey results: (a) Concept of plastic circularity; (b) life cycle of plastics; (c) mechanical and chemical recycling techniques; (d) environmental impacts of plastic waste; (e) polymer properties and performance (f) circular design and sustainability solutions.

Performance assessment data further reinforce these findings. As shown in **Figure 4**, students consistently achieved high marks across lecture-based assignments, quizzes, laboratory exercises, and design phases, demonstrating strong mastery of the course competencies. The relatively tight score distributions in most assignments indicate that students were able to engage meaningfully with the material despite diverse academic backgrounds. All students earned almost a full score on the final presentation and written report, which were evaluated using a mastery-based rubric aligned with core learning outcomes. Because the course incorporated structured milestones and formative feedback prior to final report submission and presentation, all students were able to meet the established performance criteria by the end of the term.

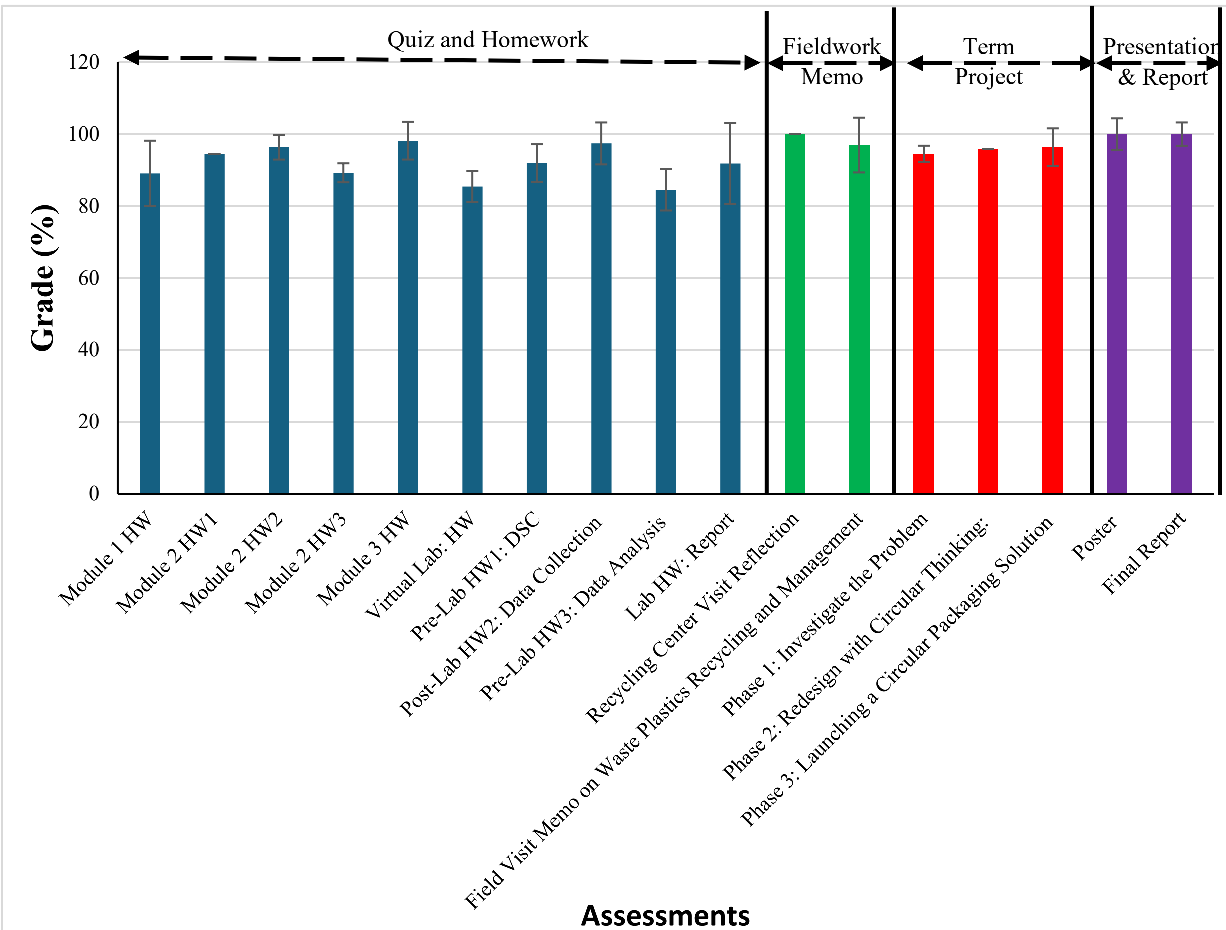

Figure 4. Student performance across course assignments, including lecture-based tasks, laboratory activities, field reflections, and multi-phase circular design projects.

Relatively lower averages were observed in three components: the virtual flexural test lab assessment, the polymer chemistry (DSC/FTIR) pre-lab data analysis assessment, and the Phase 1 system-mapping redesign term project. These tasks required unfamiliar technical skills, polymer knowledge, and data interpretation, or open-ended problem exploration, naturally increasing cognitive demand. Rather than indicating deficiencies, these results highlight areas where additional scaffolding and preparatory support could further enhance learning, particularly for students without prior exposure to polymer science or materials engineering.

3.2 Qualitative Analysis

Open-ended survey responses and focus group interviews were analyzed using thematic content analysis. Student comments were independently coded for recurring ideas related to motivation, learning experiences, challenges, and suggestions, and the resulting codes were then grouped into broader themes. Several key themes emerged from this process.

Students consistently described strong motivation and interest in the course, noting that it deepened their understanding of sustainability, circularity, and materials science. Many expressed that the course helped them connect concepts of plastic circularity to their future careers and research. As one student explained, the course *"gives a glimpse of the future world that we are going to step, probably like within one year, 2 year, or a few months. So, yeah, so in that case, this is what sort of like made us understand, okay, how this course can be related to our research or future professional life."*

Students also identified experiential learning components like field trips, laboratory sessions, and instructional videos embedded with interactive quizzes as the most valuable learning components. These activities together with interdisciplinary collaboration reinforced understanding, maintained engagement, and helped students monitor their progress. Existing literature [17], [23], [26], [30] on circular economy education identifies experiential, project-based, and case-based learning as particularly effective for promoting systems thinking and deep conceptual understanding, consistent with the learning outcomes observed in this course.

Several students also emphasized that the interactive video lecture format, in particular, made the online learning experience more dynamic and effective. Despite these strengths, students also articulated several challenges. Some found the broad scope of the course and the complexity of polymer chemistry difficult at first, although they reported that these topics became more manageable as the course progressed. The virtual laboratory facilities also presented difficulties due to the online delivery format, which restricted opportunities for hands-on experimentation.

In addition to these challenges, students provided several constructive suggestions for enhancing the course. They recommended expanding hands-on learning opportunities, integrating additional AI-based support tools, and incorporating more real-world case studies. These enhancements, they noted, would help them better connect theoretical concepts to practical applications and further enrich the overall learning experience.

3.3 Evaluation from Faculty

To complement the student evaluation, four faculty members who taught modules in the Plastic Circularity course were interviewed to gather insights about instructional design, course implementation, interdisciplinary collaboration, and future improvements. Faculty interviews were transcribed and analyzed using qualitative thematic analysis. Each transcript was coded for patterns related to student learning, course structure, instructional challenges, and recommended enhancements, and the codes were compared across instructors to identify shared observations and distinct perspectives.

Overall, faculty reported that students demonstrated strong engagement and curiosity, particularly during applied and site-based activities. They noted that students were able to connect sustainability and circularity concepts to engineering practice, and that experiential components, along with AI-supported learning tools, encouraged deeper reflection and understanding. Similar to the students' respond, faculty also emphasized the value of interdisciplinary collaboration, highlighting how the co-teaching model brought together perspectives from chemistry, civil engineering, mechanical engineering, and systems engineering. This approach was perceived as enriching the learning experience and more accurately reflecting the complexity of real-world circularity challenges. These observations are consistent with recent studies [21], [26], [31] highlighting that plastic circularity and sustainability problems require integrated, cross-disciplinary educational frameworks to mirror interconnected material, waste, and design systems.

Despite these strengths, the assessment identified some challenges that would inform future course refinement. Similar to the student's response, faculty noted that the breadth and complexity of the course content could be overwhelming, particularly for learners without prior exposure to polymer science or life-cycle concepts. This challenge reflects broader issues documented in CE education, where systemic complexity necessitates careful pacing and structured learning pathways [24], [32]. Faculty recommendations for foundational refreshers and clearer transitions between modules underscore the importance of deliberate scaffolding in multidisciplinary, team-taught courses.

Faculty also agreed that the online delivery format introduced limitations. While students appreciated the flexibility of asynchronous instruction, limited access to physical laboratory facilities, especially mechanical testing equipment, reduced opportunities for hands-on experimentation. Although prior studies show that remote laboratories can support strong learning outcomes when carefully designed and paired with meaningful interaction [33]-[35], both student and faculty feedback suggest that remote demonstrations alone cannot fully replicate the tactile engagement and material variability necessary for deep understanding of polymer behavior and recycling processes. Faculty further reported difficulty gauging student engagement without real-time visual cues, reinforcing the need for a more intentional hybrid model that integrates well-structured remote laboratories with targeted in-person activities.

Furthermore, some faculty noted the diversity in students' academic backgrounds, which required varying levels of guidance. In a few cases, instructors observed overlaps between modules due to the multidisciplinary structure and shared teaching responsibilities. Faculty recommendations focused on improving the overall course structure and alignment. They suggested implementing clearer transitions between modules, incorporating additional real-world case-based learning, and providing more scaffolding to support students with different levels of prior knowledge. They also encouraged continuing and strengthening interdisciplinary collaboration across colleges, noting that this approach was a central asset of the course. These suggestions highlight the need for deliberate instructional integration to improve coherence, reduce redundancy, and enhance curricular flow in future iterations.

4. Conclusions and Recommendations

This study evaluated the implementation of a hybrid Plastic Circularity course that combined multidisciplinary instruction, experiential learning, and digitally supported delivery. Findings from student surveys and faculty interviews revealed that although students initially reported limited understanding, particularly in technically complex topics, consistent learning gains and positive qualitative feedback confirm that the course's structure successfully supported their progression. This demonstrates that the course effectively improved students' conceptual understanding of plastic circularity, polymer behavior, recycling processes, and circular design. The hybrid format, which integrated both physical and remote laboratories, enabled students to engage with real materials and analytical procedures while maintaining the flexibility of online learning.

At the same time, the evaluation also identified key challenges that should inform future iterations. Students reported difficulty navigating the technical depth of some modules and expressed the need for additional foundational scaffolding, particularly given the diversity of academic backgrounds. Both students and faculty noted that limited access to adequate physical engagement and laboratory facilities in the online format constrained opportunities for hands-on experimentation, especially for mechanical testing and material characterization. Faculty also identified challenges related to pacing, background variability, and occasional content overlap across modules, highlighting the need for stronger instructional coordination.

Building on these findings, several recommendations emerge. The structure and delivery of the course would benefit from clearer transitions between modules supported by brief recap videos, transition slides, or a visual course map could help students better understand how the content builds toward a comprehensive view of plastic circularity. Incorporating short foundational refreshers or pre-module knowledge checks would further support students with limited prior exposure to polymer science or life-cycle concepts. Although the hybrid format provided valuable flexibility, incorporating more interactive features, such as embedded quizzes or optional synchronous Q&A sessions, it may help sustain student engagement. Given the varied academic backgrounds of students enrolled in the course, brief foundational refreshers or pre-module knowledge checks could further support equitable learning.

Experiential and applied learning emerged as one of the most impactful aspects of the course, and strengthening this component should be a priority. Balancing remote laboratories with targeted hands-on experiments would preserve accessibility while ensuring students develop necessary tactile and analytical skills. Improving the structure and scaffolding of remote labs would also help students make clearer connections between observed data, material behavior, and circularity principles. Field trips and real-world case studies should continue to be included, with opportunities to integrate more region-specific or industry-relevant examples that deepen contextual understanding.

In addition, sustained interdisciplinary coordination among faculty is essential to maintain a cohesive learning experience. Pre-course planning meetings would help teams align module sequencing and avoid redundant content, while periodic check-ins during the semester could ensure consistency in terminology, expectations, and assessment practices. Developing shared grading rubrics that emphasize both technical rigor and sustainability reasoning would further support instructional alignment and provide clearer guidance for students. Collectively, these recommendations aim to enhance the clarity, coherence, and experiential depth of the course while maintaining its multidisciplinary strengths.

Overall, the results demonstrate that a multidisciplinary, experiential, and hybrid instructional model is well suited for teaching complex and emerging topics in plastic circularity. With targeted refinements to scaffolding, laboratory delivery, and instructional coordination, future offerings of the course can further enhance learning outcomes while preserving the flexibility and interdisciplinary strengths that define its educational value.

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Appendix

Table A1. Pre- Mid-, and Post-Course Survey Questions Used to Assess Student Knowledge, Perceptions, and Learning Outcomes

Survey Domain	Pre-Course Survey Questions	Item Type	Mid, & Post-Course Survey Questions	Item Type
Student Background	What is your current academic level? What is your major/program? Have you taken a course related to sustainability, recycling, or materials science before?	Multiple choice	What is your current academic level? What is your major/program?	Multiple choice
Knowledge Self-Assessment (1 = None to 5 = Very Familiar)	Rate your current understanding of: The concept of plastic circularity; The life cycle of plastics; Mechanical and chemical recycling techniques Environmental impacts of plastic waste; Polymer properties and performance; Circular design and sustainable solutions	Likert scale	Rate your current understanding of: The concept of plastic circularity; The life cycle of plastics; Mechanical and chemical recycling techniques; Environmental impacts of plastic waste; Polymer properties and performance; Circular design and sustainable solutions	Likert scale
Interest & Confidence (1 = Not at all to 5 = Very)	How interested are you in learning about sustainable materials and recycling? How confident are you in your ability to succeed in this course?	Likert scale	How interested are you now in learning about sustainable materials and recycling? How confident are you now in your ability to succeed in this course?	Likert scale
Attitudinal Statements (1 = Strongly Disagree to 5 = Strongly Agree)	I believe understanding plastic circularity is important for engineers and scientists.	Likert scale	I believe understanding plastic circularity is important for engineers and scientists.	Likert scale
Reflection & Motivation	What do you hope to learn or achieve in this course? What aspects of this course are you most excited or curious about?	Open-ended	What is one concept or skill you learned in this course that you found most valuable? Which module(s) or activities did you find most engaging, and why?	Open-ended
Suggestions & Feedback	-	-	What suggestions do you have for improving this course? Would you recommend this course to a peer? Why or why not?	Open-ended