



# Educating Chemical Engineers for a Sustainable Future: Embedding Sustainability in Process Design

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## Abstract

Preparing future Chemical Engineers to address complex sustainability challenges requires educational approaches that move beyond traditional discipline-focused teaching to develop systems thinking, interdisciplinary collaboration, professional identity, and the ability to balance competing environmental, economic, societal, and technical priorities. However, integrating these interconnected competencies meaningfully into engineering curricula remains a significant pedagogical challenge. This paper presents a teaching-focused case study demonstrating how sustainability-driven, problem-based learning can address these challenges through a third-year Chemical Engineering Design Project centred on developing a bio-based styrene production process.

A collaborative, research-informed learning approach was adopted, enabling students to design an integrated process combining conventional ethylbenzene dehydrogenation with bioethanol production from agricultural residues. Students applied process modelling, material and energy integration, process safety and hazard analysis, and techno-economic evaluation to explore the complex trade-offs involved in sustainable industrial process design.



The educational experience highlighted opportunities to enhance student engagement, strengthen systems thinking, and develop a deeper appreciation of the interconnected technical, environmental, and economic dimensions of engineering decision-making. The project also provided opportunities for students to develop confidence in addressing open-ended problems, collaborative problem-solving skills, and professional competencies relevant to contemporary engineering practice.

Aligned with the conference theme, *Together through Change*, this case study illustrates how authentic, sustainability-led design projects can bridge the gap between theoretical learning and professional engineering practice. It offers a transferable educational approach for embedding sustainability into Chemical Engineering curricula while fostering interdisciplinary thinking, professional identity, and the competencies required to contribute to the transition towards low-carbon, resource-efficient, and sustainable industrial systems.

## Introduction

Preparing future Chemical Engineers to address increasingly complex sustainability challenges requires educational approaches that extend beyond traditional discipline-focused teaching and develop systems thinking, interdisciplinary collaboration, critical decision-making, and professional competencies. While conventional teaching provides essential theoretical and technical foundations, opportunities to integrate environmental, economic, societal, and safety considerations into authentic engineering problems can be limited. A key pedagogical challenge is therefore to bridge the gap between theoretical knowledge and its practical application, enabling students to evaluate competing design priorities, navigate uncertainty, and develop sustainable engineering solutions. Sustainability-driven, problem-based learning offers an effective approach to addressing this challenge by engaging students in collaborative, open-ended projects that reflect the complexity of real-world industrial practice.

This paper examines the integration of sustainability into a third-year Chemical Engineering Design Project through a collaborative, research-informed, problem-based learning approach. The pedagogical rationale was to provide students with an authentic industrial challenge requiring them to apply and integrate knowledge acquired across their degree programme, including reaction engineering, separation processes, process integration, safety, environmental sustainability, and techno-economic evaluation. Rather than treating sustainability as a separate topic, the project embeds it within engineering design decisions, encouraging students to critically evaluate technical feasibility alongside environmental impacts, resource efficiency, economic viability, and broader societal considerations. This



approach aims to strengthen systems thinking, interdisciplinary problem-solving, teamwork, and professional judgement while preparing students for the evolving demands of sustainable engineering practice.

The design of a sustainable styrene production process was selected as a case study because it combines an established, commercially significant chemical manufacturing route with opportunities to investigate renewable feedstocks, process decarbonisation, and circular resource utilisation. Global styrene production reached approximately 42 million tonnes in 2024 and is projected to grow at a compound annual growth rate (CAGR) of 4.37% through 2035 [1]. India, the world's largest styrene importer, with an annual trade value exceeding USD 1 billion [2], provides a relevant industrial context for exploring sustainable domestic production. Conventional styrene manufacture relies heavily on fossil-derived ethylene and energy-intensive processes, contributing to greenhouse gas emissions and presenting significant challenges for industrial decarbonisation [3]. These considerations make styrene production a suitable educational case for examining the interconnected technical, environmental, and economic dimensions of sustainable process design.

Within this context, students investigated the design and feasibility of an integrated, low-carbon styrene production plant in Gujarat, India, combining established ethylbenzene dehydrogenation with bio-based feedstock processing. Unlike alternative biosynthetic pathways employing renewable-sugar-derived L-phenylalanine [4,5], the proposed process utilises locally available corn stover to produce bioethanol through fermentation. The resulting bioethanol is used in the alkylation of benzene to produce ethylbenzene, which is subsequently dehydrogenated to styrene. Using agricultural residues offers opportunities to reduce dependence on food-based feedstocks traditionally employed in bioethanol production [6]. The project also incorporates material and energy integration, process-stream reuse, and by-product valorisation, enabling students to explore opportunities for minimising waste, improving resource efficiency, and reducing the environmental footprint of chemical manufacturing.

The principal educational objective of this case study is to demonstrate how sustainability-led, collaborative process design can provide an integrated learning experience that connects theoretical understanding with industrial application. By engaging students in evaluating complex design trade-offs and developing technically feasible, economically informed, and environmentally responsible solutions, the project aims to foster critical thinking, systems-level understanding, professional identity, and confidence in addressing open-ended engineering challenges. Aligned with the conference theme, *Together through Change*, this paper presents a transferable educational approach for embedding sustainability



meaningfully into Chemical Engineering curricula and preparing graduates to contribute to the transition towards low-carbon, resource-efficient industrial systems.

## Research Objectives and Pedagogical Approach

The primary objective of this study is to examine how a collaborative, research-informed, problem-based learning (PBL) approach can meaningfully integrate sustainability into a third-year Chemical Engineering Design Project, strengthening students' ability to apply theoretical knowledge to complex, real-world engineering challenges. The approach was adopted to address a key pedagogical challenge: enabling students to move beyond discipline-specific knowledge towards integrated systems thinking, critical decision-making, teamwork, and professional judgement while balancing technical, environmental, economic, and societal considerations.

The learning approach was structured around an authentic, open-ended industrial design challenge in which students worked collaboratively to develop a sustainable styrene production process using bioethanol derived from agricultural residues. Problem-based learning was embedded by requiring students to investigate alternative process routes, critically evaluate technical and sustainability trade-offs, integrate knowledge from different Chemical Engineering disciplines, and justify their design decisions using scientific literature, engineering principles, and process analysis. The research-informed dimension encouraged students to engage with contemporary developments in sustainable chemical manufacturing and apply relevant research findings to their design solutions.

The project was designed to integrate sustainability throughout the engineering design process rather than treating it as an isolated learning component. Students were expected to consider feedstock selection, process efficiency, material and energy integration, waste minimisation, process safety, and techno-economic feasibility as interconnected design requirements. The selected case study involved valorising corn stover through an integrated biorefinery approach (Figure 1), including opportunities for black-liquor valorisation, chemical recovery, CO<sub>2</sub> utilisation, and lignin recovery [7,8]. These elements provided opportunities for students to explore circular economy principles and assess the implications of engineering decisions for sustainable industrial development. The proposed bioethanol production pathway is illustrated in Figure 2.

The intended educational outcomes were to develop students' systems-level understanding of sustainable process design, strengthen collaborative problem-solving and evidence-based decision-making, and enhance their confidence in addressing open-ended engineering



challenges. By connecting research-informed learning with authentic industrial practice, the study aims to demonstrate a transferable pedagogical approach for embedding sustainability within Chemical Engineering education and preparing graduates for the evolving professional demands of a low-carbon, resource-efficient chemical industry.

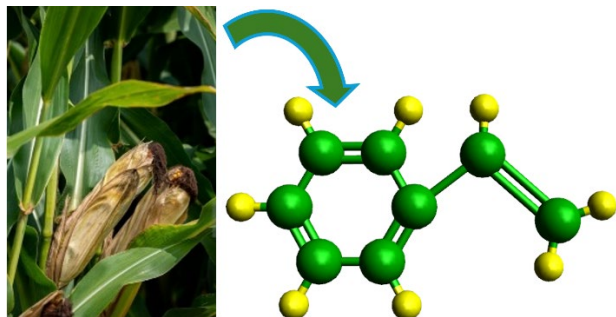


**Figure 1: Corn stover to styrene production**

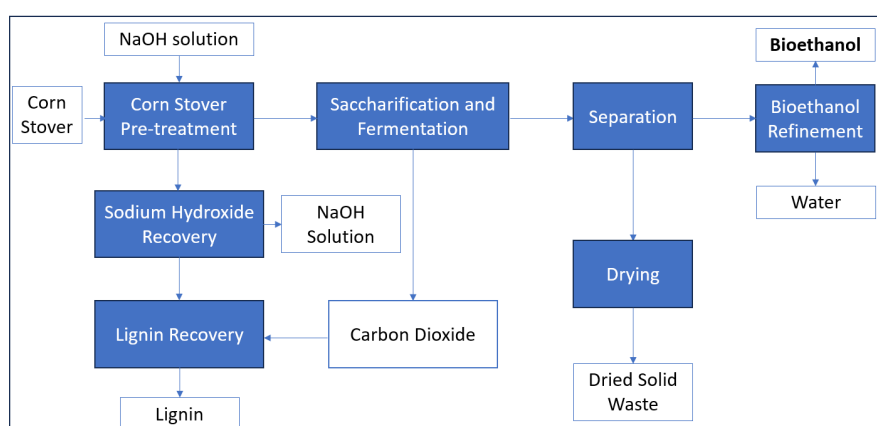


**Figure 2: Block diagram of the proposed bioethanol production plant**

## Educational Significance

This study highlights the educational value of embedding sustainability, systems thinking, and professional practice within a core Chemical Engineering Design Project through a collaborative, problem-based learning (PBL) approach. Treating sustainability as a standalone topic can limit students' understanding of its interconnected role in engineering decision-making, whereas integrating it throughout the design process encourages students to consider environmental, economic, societal, and technical implications collectively. The PBL approach addresses this challenge by engaging students in an authentic, open-ended industrial problem requiring the application of fundamental principles of reaction engineering, separation processes, heat integration, process safety, and economic analysis to develop a sustainable styrene production process.

The project incorporates bio-based feedstocks, waste valorisation, circular economy principles, process integration, recycling, and energy recovery, enabling students to explore



how sustainability considerations influence practical engineering decisions. Importantly, students must critically evaluate competing design priorities, recognising that improvements in environmental performance or resource efficiency may involve economic, technical, or operational compromises. Such evaluations encourage evidence-based reasoning, systems thinking, and an appreciation of the complexities inherent in sustainable process design. Incorporating realistic industrial considerations, including site selection, supply-chain resilience, hazard mitigation, and economic feasibility, further connects theoretical knowledge with professional practice, requiring students to justify design choices under practical constraints and uncertainty. This process aims to strengthen professional judgement, collaborative problem-solving, and responsible decision-making.

Aligned with the UN Sustainable Development Goals, this approach offers a transferable pedagogical framework for integrating sustainability meaningfully into Chemical Engineering education, preparing graduates to contribute to the **development of resilient, low-carbon, resource-efficient, and commercially viable industrial processes**.

## Implications for Chemical Engineering Education

A comprehensive process design and techno-economic feasibility assessment of a sustainable styrene production plant integrating corn stover-derived bioethanol has recently been published [9]. This case study demonstrates the value of embedding **sustainability-led, industry-relevant challenges** within Chemical Engineering Design education. Integrating renewable feedstocks, waste valorisation, circular economy principles, process safety, and techno-economic assessment within conventional process design enables students to develop **systems thinking** while balancing technical performance, environmental impact, safety, and economic viability. The approach provides a flexible pedagogical framework for capstone and project-based modules, strengthening competencies in process synthesis, material and energy integration, reactor and separation design, hazard analysis, and professional decision-making.

Importantly, the project promotes **interdisciplinary learning** by integrating chemical engineering with biotechnology, environmental science, economics, risk assessment, and social sustainability. Students experience how biological and conventional chemical processes can be integrated within complex industrial systems while considering life-cycle impacts, supply-chain resilience, location-specific constraints, and stakeholder priorities. By demonstrating that sustainability can complement technical and economic viability, this approach challenges conventional perceptions. It prepares **ethically responsible**,



**multidisciplinary, industry-ready graduates** capable of driving innovation towards low-carbon, circular, and resource-efficient industries.

## Key Design Outcomes and Educational Implementation

The sustainability-led, problem-based learning (PBL) approach has been embedded within the third-year Chemical Engineering Design Project at Lancaster University for several years, typically involving 35–42 students annually. Students undertake an authentic, industry-relevant design challenge in mixed-ability groups, enabling them to integrate theoretical knowledge, research-informed approaches, and sustainability considerations into practical engineering solutions. Group membership is organised to ensure a balanced distribution of academic abilities, with each group including at least one academically strong student and, where practicable, an appropriate balance of BEng and MEng students and gender representation. This approach also reflects feedback from previous cohorts favouring randomly allocated, mixed-ability groups, encouraging peer learning, collaborative problem-solving, and inclusive teamwork.

The project is supported through academic supervision, structured design activities, and opportunities for technical discussion and feedback throughout the design process. Academic guidance focuses on process development, engineering calculations, sustainability considerations, safety, and techno-economic evaluation, while students retain responsibility for investigating alternatives, making design decisions, and justifying their proposed solutions. The present case study was undertaken by four student co-authors under the supervision of the corresponding author, illustrating the collaborative and research-informed nature of the learning experience.

The assessment framework combines individual and group-based components to recognise both independent achievement and collaborative contributions. Individual coursework accounts for 45% of the overall mark, while an individual oral assessment contributes a further 15%. Groupwork represents 30%, and the group presentation contributes 10%. Thus, 60% of the assessment is based on individual performance, providing clear evidence of each student's technical understanding, analytical capability, and professional judgement, while the remaining 40% recognises teamwork, collaborative design, and communication skills. This balanced assessment structure supports individual accountability within a collaborative learning environment and aligns with the principles of outcomes-based assessment underpinning IChemE accreditation.



The student design project delivered an integrated, sustainability-focused styrene production process combining conventional ethylbenzene dehydrogenation with bioethanol derived from agricultural corn stover. Two-phase simultaneous saccharification and fermentation achieved a reported bioethanol yield of up to 477 kg per tonne of corn stover, providing a renewable feedstock for downstream ethylbenzene and styrene production. The proposed process achieved 95% ethylbenzene conversion and 96.2% styrene selectivity, supported by extensive benzene recycling and heat recovery, with a designed production capacity of 220,000 tonnes per year. Strategic site selection in Gujarat considered biomass availability, industrial infrastructure, skilled labour, economic feasibility, and regional development. Process safety was incorporated through fire prevention, gas monitoring, hazard assessment, and appropriate chemical-handling measures.

Beyond these technical outcomes, the project illustrates how an authentic industrial design challenge can integrate sustainability, process safety, waste valorisation, resource efficiency, and techno-economic decision-making within a collaborative educational framework. By requiring students to evaluate alternative solutions, balance competing design priorities, and justify engineering decisions, the approach provides opportunities to strengthen systems thinking, interdisciplinary collaboration, professional judgement, and communication skills. The combination of structured academic support, mixed-ability teamwork, and balanced individual and group assessment offers a transferable model for sustainability-led Chemical Engineering design education, preparing graduates to contribute to low-carbon, circular, and socially responsible industrial development.

## Conclusion

This case study demonstrates the potential of sustainability-led, problem-based learning to integrate technical, environmental, economic, and societal considerations within Chemical Engineering design education. The proposed bio-based styrene production process achieved high conversion and selectivity, with an estimated tenfold reduction in CO<sub>2</sub> emissions compared with conventional production, supported by material and energy integration, recycling, waste valorisation, and life-cycle assessment. An estimated Internal Rate of Return (IRR) of 28% further highlights the potential compatibility of environmental sustainability and commercial viability. Incorporating regional biomass resources, supply-chain resilience, societal considerations, and the *Make in India* initiative provided an authentic industrial context for developing systems thinking and responsible engineering decision-making, aligned with UN Sustainable Development Goals 7, 12, and 13.



Implementing this interdisciplinary approach presents pedagogical challenges, particularly in coordinating diverse technical and sustainability requirements, balancing individual and collaborative learning, and providing effective academic guidance for complex, open-ended problems. These considerations highlight the importance of structured supervision, clearly defined learning outcomes, inclusive group formation, and balanced assessment strategies. Future development will focus on refining sustainability assessment, strengthening industrial engagement, incorporating structured student feedback, and exploring wider application across Chemical Engineering design modules. Further evaluation of student learning outcomes will help establish the educational effectiveness and transferability of the approach.

Ultimately, this case study illustrates how authentic, sustainability-driven engineering challenges can connect theoretical knowledge with professional practice, fostering interdisciplinary thinking, strengthening professional identity, and preparing future Chemical Engineers to address emerging challenges in low-carbon, circular, and resource-efficient industries.

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