Integrating Sustainability Principles into a Chemical Engineering Laboratory Curriculum

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Abstract

Integrating sustainability into the chemical engineering curriculum prepares students to become forward-thinking engineers by applying sustainability principles to fundamental concepts. They learn how to design eco-friendly products and processes that incorporate Green Chemistry Principles and circular economy indicators. In our program at the [name redacted], we align these efforts with the United Nations Sustainable Development Goals, the Paris Agreement, and the [name redacted] net-zero mandate, ensuring students are equipped to tackle global challenges. Through practical exercises and structured support, students learn to apply sustainable engineering concepts to real-world problems. Vertical and horizontal integration across years enables progressive skill development, connecting theory to practice through laboratory education.

Guided by the 12 Graduate Attributes (GA) established by the Canadian Engineering Accreditation Board, we continuously improve curriculum quality to bridge knowledge and skills gaps between classroom and industry. Our modernized laboratory curriculum strengthens student competencies in Problem Analysis (GA2), Investigation (GA3), Use of Engineering Tools (GA5), Communication Skills (GA7), and Professionalism (GA8).

In this work, we highlight our approach to integrating sustainability into laboratory education through biodiesel production projects. In second year, students study the chemistry of biodiesel production at the bench scale, analyze product quality using spectroscopic techniques, and evaluate yield, safety, environmental impact, and cost. Building on this foundation, third-year students optimize biodiesel production in pilot-scale reactors in our Unit Operations Laboratory, applying simulation software to design and optimize reactor systems and operating conditions.

Through these integrated projects, students connect knowledge across organic chemistry, thermodynamics, heat and mass transfer, separation processes, process design, sustainability, and safety. Using biodiesel production as a mechanism for integration, students see the intersection of applied chemistry and chemical

engineering and recognize the direct impact of sustainable practices on the environmental sector and broader industry.

1 Introduction

As a signatory to the Paris Agreement, Canada aims to reduce emissions by 40-45% by 2030 compared to 2005 levels. Clean fuels, including biodiesel, play an important role in achieving this target, especially with the federal Clean Fuel Standard, which require suppliers of liquid fossil fuel to reduce their carbon intensity by 15% by 2030. Therefore, research into biodiesel, an organic, non-toxic, and biodegradable fuel made from renewable feedstocks is more important than ever in Canada and globally.

Incorporating sustainability concepts into the lab curriculum enables students to gain hands-on experience tackling 21st century challenges, preparing them for relevant careers in industry. While the fossil fuel industry transitions over time to cleaner fuels and technologies, biodiesel research can help reduce emissions in the short-term using existing equipment that the industry is already familiar with (e.g. batch reactors, separation equipment, etc.). Given our department's contributions to biodiesel production in Canada, particularly through the innovations of Professor Emeritus David Boocock (The Engineering Newsletter, 2008), this process was chosen to integrate sustainability concepts into our curriculum.

This paper presents a laboratory-focused initiative that integrates sustainability principles into two core laboratory courses at the [name redacted] in years 2 and 3. Using biodiesel production as the central theme, the initiative aims to enhance the student experience and train chemical engineering students in developing biodiesel from sustainable resources. The paper examines the current vertical integration of sustainability – specifically through biodiesel-related content – within undergraduate engineering curriculum, identifies existing gaps, outlines our instructional approach, reflects on key learnings, and proposes directions for future development.

2 Literature Review

Engineering as a degree, aims to equip students with the technical expertise and critical thinking skills needed to address complex global challenges. Among these challenges, sustainability and resilience have emerged as an essential priority, as seen through the United Nations Sustainable Development Goals (SDGs) (United Nations, n.d.). However, despite increased efforts to include sustainability in the engineering curriculum, many engineering programs struggle to significantly integrate it with hands-on learning experiences. This literature review explores current innovations in chemical engineering curriculum and contrasts existing methods in comparison to the integrated, two-year biodiesel project (herein referred to as the Biodiesel Project Labs) in this paper, which emphasizes sustainability and green chemistry principles, experiential learning, and inquiry-based problem solving.

2.1 Disconnect Between Laboratories, Sustainability Integration, and Practical Application

Current engineering curriculum often introduces sustainability through lectures, case studies, or design projects (Chintalapati, 2022), referred to as Lecture-Based Learning (LBL). While valuable, this style of teaching can leave students with only a theoretical understanding but limited thinking of how to integrate sustainable solutions in real-world engineering practice (Ghaemi & Potvin, 2020). Research shows that students frequently struggle to connect challenging concepts to their professional responsibilities as engineers (Wilson *et al*., 2023).

Traditional lab-based courses are often presented in an expository manner ("recipe-style" approach), allowing students to verify fundamental theories but offer little opportunity to analyze the relevance of a lab and its application. This limits metacognitive development and knowledge retention for students. In contrast, Inquiry-Based Learning (IBL) and Problem-Based Learning (PBL) foster engagement, critical thinking, and problem-solving by challenging students to actively research, integrate, and apply knowledge to complex sustainability challenges, rather than blindly following instructions. Research has confirmed the importance of IBL and PBL within engineering lab courses and the benefits that students gain from it (referenced below). However, there has been limited research to incorporate real-world sustainability challenges into laboratory experiments through IBL and PBL, highlighting a critical gap in academia that needs to be addressed.

Chintalapati et al. reports increased engagement and understanding when traditional expository labs were replaced with open-ended procedures (Chintalapati, 2022). This shift forced students to think critically and apply existing knowledge rather than simply following a prescribed procedure. Also, another study by Ghaemi et al. on fourth-year students using PBL, found that students appreciated having autonomy over experimental design; helping them understand why processes and design matter, rather than focusing solely on obtaining results to write their report (Ghaemi & Potvin, 2020). Both papers demonstrate the importance of experiential learning, and the impact it has on creating connections between theory and practice, however, neither of them connect IBL and PBL with sustainability concepts.

Similarly, a study of first-year engineering students that participated in sustainability-focused design projects found that, although students understand the importance of sustainability and green initiatives, they struggled to see how it applied to their profession (Vaez Ghaemi *et al.*, 2024). This study highlights the limited integration of IBL, PBL, and sustainability within the engineering curriculum.

Laboratory-based courses offer an excellent opportunity to bridge experiential learning approaches, such as IBL and PBL, with sustainability principles (Austen *et al.,* 2022). These experiences help students grasp the real-world importance of sustainability and understand how their experimental work connects to the global challenges they will face in industry.

2.2 Alignment with the Global Sustainable Initiatives

During a national workshop entitled "*Exploring Opportunities in Green Chemistry and Engineering Education: A Workshop Summary to the Chemical Sciences Roundtable",* sponsored by the National Research Council, it was recommended to include Green Chemistry in undergraduate engineering curriculum (National Research Council US, 2007). The 12 Principles of Green Chemistry, developed by Anastas and Warner in 1998 provides a framework for incorporating sustainability into chemical engineering curriculum. Also, Green Chemistry is applicable throughout the life cycle of a chemical product / process, including its design, manufacturing, and use. While Green Chemistry has been integrated into chemistry education, there are fewer examples of its incorporation within the engineering curriculum (Etzkorn & Ferguson, 2022).

2.3 Comparison with Existing Models

Based on our research, IBL and PBL are effective approaches for lab-based education. While many studies discussed the benefits of these pedagogical frameworks, few demonstrate the vertical integration across years of study, as seen in our project. Similarly, while sustainability concepts are introduced in lectures or through isolated assessments (e.g., case studies or green chemistry metrics), there is limited integration / explanation to real-world applications or how these theories and tools apply to industrial practices (Bilgin *et al.,* 2023). Our project incorporates two sustainability frameworks: Green Chemistry Principles 2, 3, 5-7, and 9 (Anastas *et al.*, 2007), and the United Nations SDGs 7, 12, and 13 (United Nations, n.d.). Sustainability concepts were "built-in" to lesson plans and experiments rather than "add-ons" (Huntzinger *et al.,* 2007), helping students understand how to design more resource-efficient and safer processes and products.

To our knowledge, no other program uses biodiesel production as the mechanism for teaching and learning sustainability concepts in a lab setting that is vertically integrated across the curriculum. Our scaffolding approach requires students to engage in continuous, collaborative problem-solving. Rather than simply learning about biodiesel as a renewable fuel, students engage in creative, team-based problem solving that mirrors industry practice. It builds on students' knowledge over time, driving them to work through challenges and troubleshoot issues together, as a set of engineers together.

3 Methodologies – Curriculum Design and Integration Strategy

The Biodiesel Project Labs were developed utilizing IBL and PBL to enhance experiential learning and reinforce core chemical engineering concepts within the framework of sustainable engineering. This section outlines the course descriptions, educational frameworks and principles used in the design of the lab activities, and alignment with accreditation and graduate attributes.

3.1 Overview of Core Laboratory Courses and Structure

Two core laboratory courses were selected for the Biodiesel Project Labs: CHE205S – Chemical Engineering and Applied Chemistry Laboratory II and CHE305S - Chemical Engineering and Applied Chemistry Laboratory IV. Second-year labs operate on a biweekly basis, with 2h of lecture time in week one, followed by 6h of wet labs in week 2. Lectures provide students with opportunities to explore theory, prepare for labs, and analyze data. Third-year labs operate weekly with 6h of contact time. These courses were chosen because they align closely with core subjects that teach fundamental concepts related to lab activities.

The second-year laboratories focus on analytical and organic chemistry, equipping students with fundamental chemistry knowledge, synthetic techniques, and analytical skills at bench scale. Majority of experiments are completed individually, allowing students to master foundational laboratory techniques and skills. This prepares them for the third-year Unit Operations Laboratory (UOL) courses, where students work in small groups of 4-5 people, learning how to operate industrial and pilot-scale engineering process equipment. In these labs, students apply and integrate core engineering concepts and principles, including fluid statics and dynamics, heat and mass transfer, thermodynamics and phase equilibria, chemical kinetics and reactions, and separations. These labs also develop skills in trouble shooting, process scale-up design and optimization, data analysis, and process safety.

3.2 Experimental Design Approach

Development of lab activities were guided by constructivist learning theory, where students 'learn by doing' to build an understanding of sustainability concepts through hands-on experience, reflection, and inquiry. Two pedagogical frameworks were used to design the Biodiesel Project Labs: IBL and PBL. Experiments were designed to engage students in questions of material and resource use, scalability, environmental impact, safety, and process efficiency, introducing concepts such as SDGs, Green Chemistry Principles, and circular economy indicators while simultaneously teaching core concepts (e.g., chemical reactions, thermodynamics, separation processes). Through iterative experimentation, collaborative data analysis, and group discussions, students develop the ability to apply their sustainability concepts to design biodiesel from sustainable resources. Key design principles included:

- **Progressive Learning Across Academic Years**: Second-year students study biodiesel chemistry, reaction kinetics, and the effects of reactants. In third year, they produce biodiesel at the pilot scale, optimizing chemical processes for safety and sustainability. Students also conduct life cycle analyses and use Aspen Plus to design large-scale plants through problem-based scenarios, such as fueling commuter buses.
- **Open-Ended Design**: Students use design of experiments to explore variables such as feedstock type, reaction temperature, catalyst, purification and characterization methods.
- **Incorporating Sustainability Metrics Through Experimentation**: Students consider waste reduction, catalyst type, atom economy, and material sourcing as part of process optimization.
- **Collaborative and Reflective Learning**: Data sharing and group analysis simulate industrial teamwork and foster professional communication skills.
- **Integration with professional competencies**: Aligned with the CEAB Graduate Attributes.

These principles are applied consistently across laboratory courses and are reflected in the learning objectives summarized in Figure 1. Figure 1 highlights relevant second- and third-year courses involved in the Biodiesel Project Labs, illustrating the skills acquired and how the lab sequence aligns with specific sustainability criteria outlined by global sustainable initiatives and engineering accredited standards.

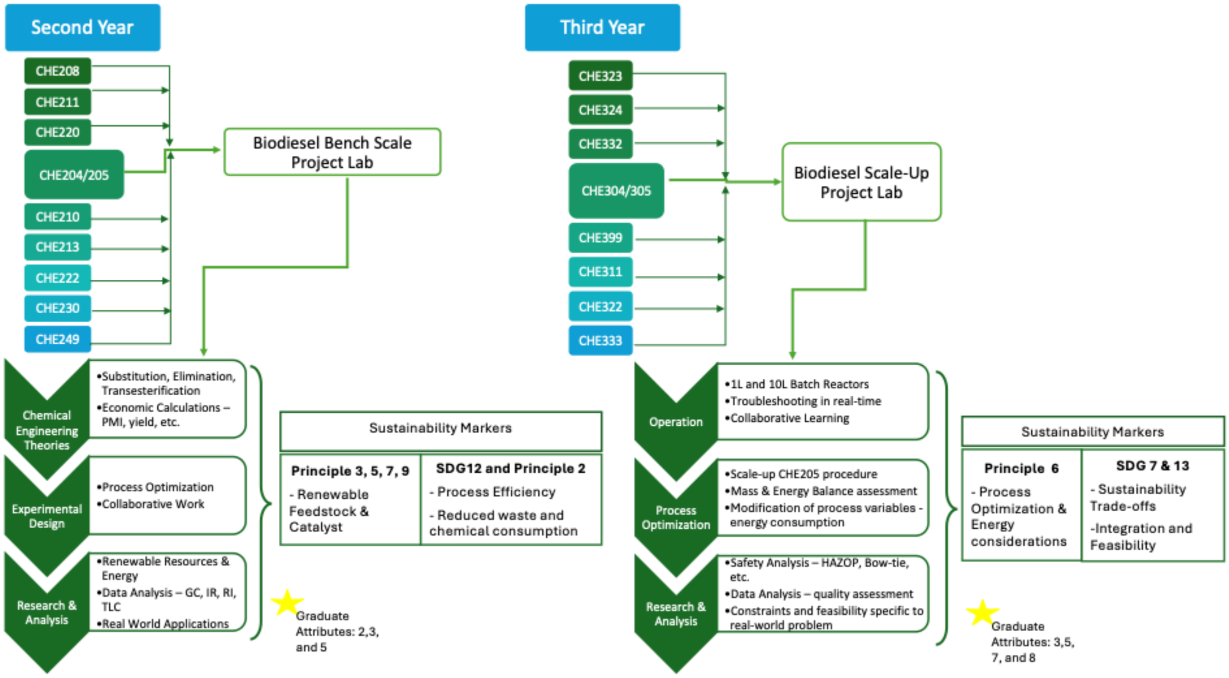

Figure 1. Summary of Course-Level Learning Objectives and Sustainability Integration

3.3 Alignment with Accreditation and Graduate Attributes

The Biodiesel Project Labs aligns with the Canadian Engineering Accreditation Board (CEAB) Graduate Attributes (GA), which emphasize the development of broad engineering competencies beyond technical knowledge. Table 1 outlines how the developed lab sequence supports the development of each GA.

Table 1. Achievement of Graduate Attributes through Course Activities

Graduate Attribute	**Achievement Method**
GA2: Problem Analysis. Demonstrate the ability to formulate a solution plan (methodology) for an engineering problem.	Design of experiments and process troubleshooting.
GA3: Investigation. Demonstrate the ability to devise and execute a plan to solve a problem.	Data collection, analysis, and optimization studies.
GA5: Use of Engineering Tools. Demonstrate ability to use fundamental modern techniques, resources and engineering tools.	Use of various laboratory instruments and Aspen Plus.
GA7: Communication Skills. Demonstrate the ability to identify and credibly communicate engineering knowledge.	Written reports and collaborative data discussions.
GA8: Professionalism. Demonstrate the ability to describe engineering roles in a broader context, e.g. as pertains to the environment, health, safety, and public welfare.	Adherence to safety practices, ethical reflection, and environmental responsibility.

4 Discussion

The following section describes the Biodiesel Project Labs implemented into the second- and third-year laboratories. Lab activities progressively build on foundational knowledge, practical skills, and real-world applications.

4.1 Second-Year Laboratories: Bench Scale Biodiesel Production and Process Optimization

The Biodiesel Project Lab in second-year is a term long project that invites students to explore the chemistry of the biodiesel process by examining alternate synthetic pathways at bench scale. In class, students learn the fundamental chemistry of biodiesel production, focusing on the transesterification reaction which converts triglycerides and alcohols into esters (biodiesel) and glycerol (byproduct) in the presence of a catalyst. Through independent research, students study the role catalysts play in lowering the activation energy to enable faster reactions at lower temperatures in both base- and acid-catalyzed processes. They also learn how the base-catalyzed process can form free fatty acids (FFA), while acid catalysis can convert FFAs to biodiesel through Fischer esterification. To address the reaction's equilibrium limitations, students must apply prior knowledge of Le Chatelier's principle, using excess alcohol to drive the conversion to completion.

Working collaboratively, in self-selected teams, they develop a class optimization study using methods such as design of experiments, investigating different reaction conditions (e.g., oil type, catalysts, temperatures, reactant ratio, etc.) as well as work-up procedures to determine the optimal chemical process. Over two 6h laboratory sessions, students apply chemical and physical chemistry concepts such as organic synthesis and separations to produce biodiesel. They assess the quality using analytical techniques such as thin layer chromatography, infrared spectroscopy, titration, and gas chromatography. In their final reports, students reflect not only on chemical performance but also on factors such as chemical safety, environmental impact, and reagent cost—prompting early systems-level thinking and awareness of sustainable design considerations. This autonomy requires them to apply chemical engineering principles from other courses and encourages teamwork, communication, and critical thinking.

4.2 Third-Year Laboratories: Pilot Scale Biodiesel Production

In third year, students revisit the biodiesel production experiment in the UOL with a new focus on PBL. It is one of ten laboratory projects that spans four weeks – one week of the core lab that all students must complete and three weeks for the specialization lab (of their choice). In the core lab, students analyze the biodiesel produced in second year, evaluating key parameters such as enthalpy of formation, heat of combustion, conversion rates, and yield. Using pooled experimental data from varying conditions (e.g., temperature, reactant types, and concentrations), students design a process to scale production to larger quantities (e.g., 1 L). As the complete the labs, they deepen their understanding of thermodynamic drivers and use process simulation software like Aspen Plus to optimize reactor design and production processes aimed at real-world targets, such as providing fuel for a commuter bus. As part of the specialization labs, two projects are related to the production of biodiesel: 1) biodiesel production and process scale-up design, and 2) Life Cycle Analysis (LCA) for biodiesel production. Students expand their skills by practicing LCA and chemical process safety in scaling biodiesel production to larger equipment in the Unit Operations Laboratory (10 L, 50 L, and 100 L reactors). Environmental policy, standards, and quantitative sustainability assessments are further integrated into final specialization projects during the second term of the third-year curriculum.

4.3 Implementation of Sustainability Principles in Biodiesel Project Labs

Table 2 demonstrates how key UN SDGs and Green Chemistry Principles are integrated into the Biodiesel Project Labs, highlighting specific course activities and intended outcomes.

Table 2: Mapping SDGs and Green Chemistry Principles to Class Activities

Principle / SDG	Class Activity and Outcomes
SDG 7: Affordable and Clean Energy	Investigate biodiesel as a renewable fuel and explore its application in powering public transportation. Supports clean energy transportation.
SDG 12: Responsible Consumption and Production	Track material use. Explore waste reduction and reuse of materials. Promotes responsible processes / production.
SDG 13: Climate Action	Through lab experiments, lectures, and critical research, students learn how engineering can contribute to climate change mitigation. Builds climate-conscious engineers.
Principle 2: Atom Economy	Parameter selection (catalyst, reagents, temperature) for maximum biodiesel yield, ensuring full utilization of materials.
Principle 3: Less Hazardous Chemical Synthesis	Exploring transesterification reaction that uses eco-friendly chemicals (e.g., cooking oils, ethanol) yield greener process and safer lab environment.
Principle 5: Safer Solvents and Auxiliaries	Use of eco-friendly solvents (water, ethanol, brine) in synthesis and workup. Reduced environmental footprint.
Principle 6: Design for Energy Efficiency	Investigating short reaction times (< 2h) and low reaction temperatures (< 80 ºC). Lower energy use.
Principle 7: Use of Renewable Feedstock	Selection of renewable feedstocks (waste oil, cooking oil). Support for circular economy.
Principle 9: Catalysis	Explore catalyst type and catalyst loading. Improve reaction rates.

5 Conclusion and Future Work

In this paper, we highlight the use of biodiesel production as a theme to integrate sustainability and experiential learning into the laboratory curriculum of our chemical engineering program in years 2 and 3.

In second year, students study biodiesel production fundamentals, focusing on reaction chemistry, kinetics, and the effects of different reactants through a term long, IBL project. In third year, they revisit this project through PBL, analyzing their biodiesel, designing pilot-scale (1 L) production, optimizing processes with Aspen Plus, and practicing Life Cycle Analysis and process safety. Students later scale up production to 10–100 L in the Unit Operations Laboratory. Early evidence suggests a positive impact on student learning and engagement (Goroshko *et. al.,* 2024). For example, from in-class discussions it was observed that students appreciated the opportunity to integrate engineering concepts into their laboratory work and felt more confident in areas such as project management, experimental design, equipment operation, process safety, and data analysis—key competencies for co-op and professional readiness.

Using biodiesel as the central theme, we have begun integrating sustainability concepts in years 1 through 4 (Farmer *et. al.*, 2025 unpublished). In the first-year curriculum, students explore carbon dioxide emissions, renewable energy, and biodiesel production's role in reducing carbon footprints. Through lectures and projects, they learn how repurposing waste fuels can create renewable energy sources with lower emissions compared to petroleum-based fuels. In fourth year, experiential learning culminates in Plant Design and Capstone projects, where students design biodiesel plants and apply their knowledge to real-world scenarios through prototypes, 3D models, and experiments.

Surveys assessing students' experiences with IBL and PBL, sustainability concepts, research, and design are currently being collected along with GA data. The data will be analyzed to measure the curriculum's effectiveness and guide future improvements.

For future work, we aim to collect instructor and student reflections and feedback on learning experiences, and to further expand both conceptual and practical learning through the continued use of the biodiesel production project across multiple years of the curriculum.

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