The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
ASEE
Paper ID #44146

Board 26: Reducing Environmental Impact in Higher Education: Curriculum Design for the Sustainable-Unit Operations Laboratory

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Reducing Environmental Impact in Higher Education: Incorporating Life-Cycle Analysis in the Curriculum Design for Sustainable Unit Operations Laboratory

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Abstract

As outlined in the Paris Agreement, the global commitment to achieving net-zero emissions by 2050 necessitates a multifaceted approach encompassing clean energy initiatives and carbon taxation. Higher education institutions, recognizing their role as key contributors to sustainability, are increasingly focusing on reducing their carbon footprint. The teaching laboratories, essential for various disciplines, contribute significantly to the university's carbon footprint. In this study, we applied the common practices of Life Cycle Analysis (LCA) in the industry to the Unit Operations Laboratory, which resembles the industrial settings yet focuses on teaching and learning that may not have set production scopes nor define operation conditions and processes (i.e. for learning purposes and study impact of various factors on common chemical processes). As learning is the main objective in undergraduate laboratories, LCA methodologies related to laboratory equipment and incorporating technical information on global climate initiatives, clean energy, and the Paris Agreement need to be followed, but some modifications to make such calculations possible. To illustrate the feasibility of this approach, a case study on bioethanol production through yeast fermentation and subsequent distillation processes is employed as a proof-of-concept. This case study serves as a platform for estimating LCA and redesigning experiments with the aim of reducing the carbon footprint. Since not all chemical process units are designed the same (i.e. sizes, power/production capacity), this project is a collaborative effort internationally amongst universities with similar equipment but different sizes. The carbon footprint approaches, and the preliminary data collected can enable fine-tuning and test the robustness of the approaches and models. The Unit Operations Laboratory emerges as a valuable platform for students to assess their carbon footprint and actively engage in practical LCA applications. This research contributes to the broader goal of embedding sustainability principles within the educational framework, fostering a generation of professionals equipped with the knowledge and skills necessary to address environmental challenges.

1.0 Introduction

Carbon footprint evaluation is one of the standard approaches in estimating the emission of an enterprise or an institution. Most of the life cycle analysis is done for the whole building, and each activity's contribution is recorded and analyzed [1]. They considered all greenhouse gases and expressed all emissions in terms of CO_2 equivalent. These emissions are calculated based on the amount of activity and CO_2 emission intensity. The contribution of individual research activity or undergraduate laboratory teaching is not analyzed separately. The contribution of CO_2 emission from these lab activities is essential to provide best practices or action plans to reduce CO_2 emissions. However, this area has limited research to provide easy and robust approaches to analyzing carbon footprint and drive research and experimentation design. Note that research and educational activity in higher education differs from industrial settings in that the process usually operates at the most efficient point to maximize profits. In higher education, teaching/research activities aim to understand specific processes or fulfill the identified learning outcomes, so operation conditions are often varied and can be less economical.

Teaching laboratories are essential for higher education, providing students with hands-on experience and practical application of theoretical knowledge. However, these laboratories have a significant environmental cost, contributing substantially to energy and gas emissions, water consumption, and waste production. Recognizing this, efforts to minimize the environmental impact of laboratory operations have gained momentum. The Unit Operations Laboratory, in particular, stands out as a pivotal setting for students to not only grasp the theoretical aspects of their field but also to actively engage in sustainability practices. This laboratory, commonly utilized in science and engineering disciplines, allows students to understand the practical implications of their work on the environment and provides a unique opportunity to integrate Life Cycle Analysis. LCA is a systematic approach to evaluating the environmental impacts of a product, process, or service throughout its entire life cycle, from extraction of raw materials to end-of-life disposal. It assesses resource use, emissions, and energy consumption to identify areas for improvement and inform decision-making. The ISO standards required for performing the life cycle assessment are ISO 14040 describes the "principles and framework for LCA", while the ISO 14044 "specifies requirements and provides guidelines" for LCA. ISO 14067 "specifies principles, requirements and guidelines for the quantification and reporting of the carbon footprint of a product [2]." LCA consists of three main stages: inventory analysis, impact assessment, and interpretation. Carbon footprint quantification is based on Scope 1, 2, and 3 emissions, which are categories used to classify greenhouse gas emissions associated with an organization's activities. Scope 1 emissions include direct emissions from sources owned or controlled by the organization, such as fuel combustion and process emissions. Scope 2 includes indirect emissions from purchased electricity, heat, or steam. Scope 3 emissions cover indirect emissions from sources outside of an organization's direct control, including upstream and downstream activities like supply chains, transportation, and product use [2]

In this study, we explored the application of LCA analysis to determine the baseline CO_2 emission by evaluating the existing operations and theoretical prediction of an undergraduate pilot-scale experiment-bioethanol production and distillation processes. The LCA analysis is conducted based on Scope 1 and Scope 2, following ISO 14040 and 14044 standards, using Defra GHG emission factors for 2022. Recognizing the variability in laboratory practices across different regions and institutions, international collaboration is necessary to test the robustness and scalability of common unit operations laboratory projects. Collaborative efforts can provide diverse perspectives, validate findings, and contribute to the development of standardized practices in laboratory education. Two institutions, one in Canada and one in the US, worked together to test the LCA approach on four distillation columns, a 20 ft plate and packed distillation column in Canada and 35ft plate and packed distillation columns in the US, and 2 bioreactors of 80 L in another institution and 80 L in another one. This project is ongoing and is performed by undergraduate and master's students as part of the courses they are taken or the thesis study.

2.0. Energy-Based Carbon Footprint of Sugar and Corn Syrup for Bioethanol Production

Biofuels like bioethanol and biodiesel, which can be generated from agricultural feedstock and are a more renewable and sustainable source of energy than fossil fuels, are gaining popularity. They can also be added to gasoline to reduce its emissions [3]. The Unit Ops lab, the undergraduate laboratory in the Department of Chemical Engineering at the University of Toronto would like to produce bioethanol in their bioreactor for educational purposes (i.e. conducting life cycle analysis utilizing this process). A carbon footprint study was undertaken to enable a data-driven laboratory experiment design to reduce carbon footprint by selecting an efficient feedstock for the fermentation process.

In the undergraduate laboratory curriculum, refined sugar is the most common feedstock used in bioethanol production. In this study, the student team also investigated another alternative feedstock of corn syrup based on the bioethanol conversion/yield[4,5]. Studies have shown that the amount of CO_2 generated from the chemical processes is directly proportional to the conversion rate [3]. Since corn syrup contains more complex sugar, the lag phase is comparably longer than pure sugar, increasing steam and electricity consumption. Also, modified enzymes can used for better conversion, but those enzymes are not readily available and have to be transported, which could contribute to increased carbon footprint [4,5]. Therefore, for effective feedstock comparison, most operation parameters were kept constant, including the 80L fermentor and Saccharomyces cerevisiae used as the yeast. For both feedstocks, the general bioethanol production from sugar-based feedstock can be described as [6,7]:

$$2\ C_6H_{12}O_6 + \text{Saccharomyces cerevisiae (yeast)} \rightarrow 4\ C_2H_5OH + 4\ CO_2$$

Please also note that recent technological advances have enabled alternative bioethanol production routes, utilizing carbon monoxide (CO) as the carbon source and genetically modified yeast to convert otherwise harmful CO and CO_2 emissions into biofuel[8] The Unit Operations Lab curriculum will also consider this alternative production route after process safety analysis as the production route requires additional air-handling equipment and compressed gas chemicals.

The LCA analysis for the two different feedstocks, refined sugar and core syrup used in this study is summarized in Table 1. Note the transportation for the chemicals are not taken into account in the total emission. Based on Scope 1 and 2 CO_2 emission calculations and results summarized in Table 1, Carbon Footprint from corn syrup is almost twice as that of refined sugar for half the amount of Ethanol produced and with half its concentration so from this we can say that refined sugar is better for bioethanol production.

Table 1: Summary emission data for bioethanol production via yeast fermentation [4,6,7,9 10]

Feedstock	Quantity of Feed Needed (Kg)	Ethaol Concentration (%v/v)	Ethanol Produced (L/year)	Total Energy Used (MJ/L ethanol)	Total CO_2 emission (CO_2e g/year/L ethanol)
Refined sugar	780	7.92	403	157	1,773
Corn syrup	608.4	15.49	206	317	2738

3.0. Energy-Based Carbon Footprint of Bioethanol Distillation via Packed and Plate Columns

The project scope in this part of the study is to determine and compare the carbon footprint of the distillation columns under total reflux operation and flash conditions. These two conditions represent the boundary/extreme operations (most energy-conserved and demanding conditions) to meet the defined product specs. Different heat duties applied in the form of controlling the steam pressure for a defined period of operation are studied, and CF is determined.

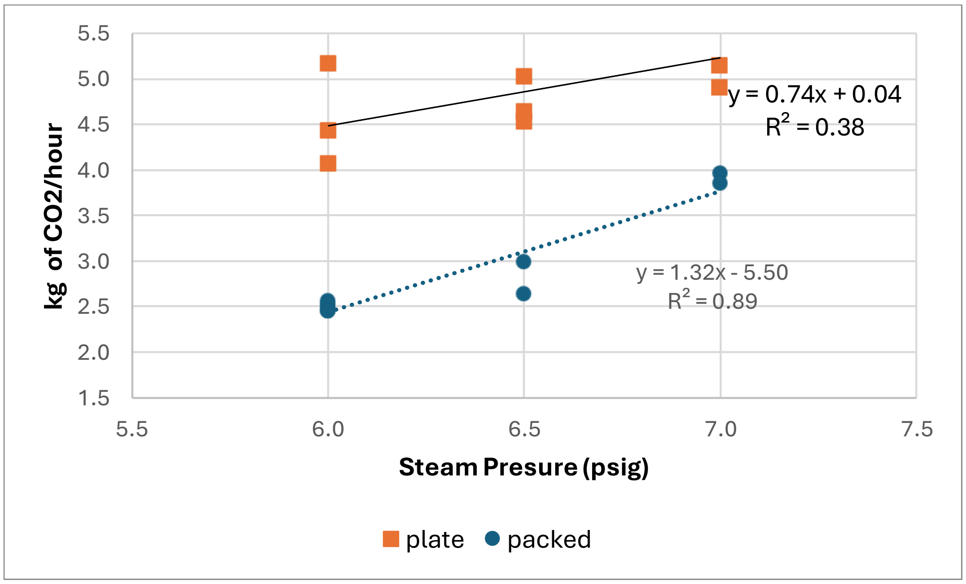

Figure 1: Carbon dioxide emission for the plate and packed distillation operation under total reflux condition.

Current experimentation design requires students to operate the packed and plate column under various reboiler duty based on adjusting steam pressures at 6.0, 6.5, and 7.0 psig. Based on the results shown in Figure 1 for operation under total reflux condition for approximately 1.5-2h, the normalized per hour emission was approximately 2.5 to 4.0 Kg CO_2/h for packed column and 4.5 to 5.3 Kg CO_2/h as steam heating with pressure increased from 6.0 to 7.0 psig. Although the incremental change on the heating pressure was not large at 0.5 psig, the emission increased by 12% when the pressure varied from 6 to 6.5 psig and an 38% increase in carbon emission when steam pressure adjusted from 6.5 to 7 psi for heating.

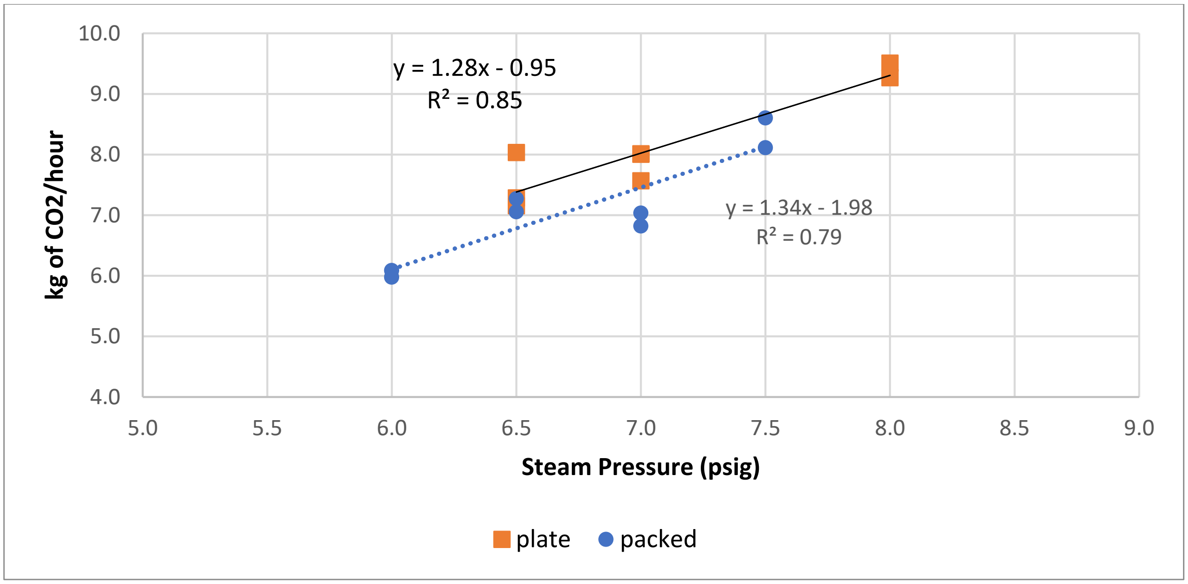

Figure 2: Carbon dioxide emission for the plate and packed distillation operation under flash condition.

When operating under flash conditions, the feed flowrate of the plate and packed column are adjusted to reach the steady state condition (note the column is not equipped with the control feedback system for education purposes so that students are required to adjust the feed, distillate and bottom product flowrate to maintain steady state condition). The maximum feed flowrate for packed and plate columns are 0.67 and 2.67 USGPM, respectively. In Figure 2, the plate and packed column showed similar emission rates ranging between 6.0 and 9.5 Kg CO_2 /h when the reboiler steam pressure increased from the set point of 6 to 8 psig. About 5 % increase in CO_2 emission when pressure changes from 6.5 to 7 psig. However, there was about 19% increase when the pressure changed from 7 to 8 psig. A similar trend was observed for the packed column. Note the total operation time to reach a steady state was within 30 min difference. This finding has prompted the consideration of operating the column with a slightly lower steam pressure for heating, yet impact minimum on the learning objectives (ie. Effect of steam pressure for reboiler on column operating performance).

Conclusion

In conclusion, this research paper demonstrates the proof-of-concept of the integration of Life Cycle Analysis into Unit Operations Laboratory curricula design. With a focus on the environmental impact of laboratory equipment operation, the paper aligns with global sustainability initiatives, clean energy efforts, and the commitment to achieving net-zero emissions by 2050. From the findings, using refined sugar with yeast for bioethanol production reduces the carbon footprint by half compared to that of corn syrup feedstock. For the subsequent purification process, simply varying the steam heating pressure for the reboiler can reduce the CO_2 emission by 20-30%, depending on the reflux or flash operating conditions. The scalability and future work section emphasizes the importance of incorporating Scope 3 emissions, including life cycle costing and creating a comprehensive teaching database.

Future Work

Future work involves expanding the study to include life cycle costing, creating a comprehensive database for LCA values and process pathways in teaching laboratories, and fostering international collaborations to test the robustness and scalability of common unit operations laboratory projects by extending similar practices to different sizes of operation equipment in other institutions. This collaborative effort aims to validate and improve laboratory practices, contributing to the broader goal of sustainability in higher education. The future work involves trying out modified enzymes for bioethanol production with increased conversion rates for different feedstock and measuring its carbon footprint with the available setup in unit operation labs.

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