Sustainable Materials Design in Undergraduate Engineering Education

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Abstract: Accelerated by rising population and consumption of resources, industries are increasing manufacturing and production to contend with demands. The resulting pollution in air and water, climate change, and lack of access to basic resources have led to a global crisis, putting our ecosystems, economy, and quality of life at risk. To mitigate these risks, sustainable materials and manufacturing processes must be developed to redesign those that solely rely on fossil fuels, generate excessive waste, or release harmful emissions. The field of materials science and engineering (MSE) is uniquely positioned to address these issues of waste management and sustainability across industries by directly influencing how products are processed, manufactured, and disposed. Engineers must possess fundamental understanding of materials, in addition to understanding of economic, social, and environmental drivers to advocate for sustainable alternatives. There are great opportunities in MSE undergraduate education to train the next generation of forward-thinking scientists and engineers, so they are prepared to address the large-scale climate change problems.

At the University of Michigan, engineering is focused on developing fundamental technical and teambuilding skills so that our engineers can redesign systems to better serve all people. This "people-first" engineering focus has led to the reshaping of the capstone design course for senior undergraduate students in MSE to focus on the economic, environmental, and social impact of advanced materials and processes. In this course, groups of five students collaborate on a materials-focused sustainability project addressing specific United Nations Sustainable Development Goals (UN SDG). The goal of the course is to provide a team environment in which each student can gain an understanding of key aspects of sustainability in materials development and engineering design, and apply relevant analysis methodologies such as life cycle assessments, techno-economic analysis, and eco-properties audits. Students use Ansys Granta Edupack to visualize and understand the economic and environmental impacts of their project to identify trade-offs in sustainable engineering decision-making and validate their solutions. Students gain skills in teamwork, critical thinking, and both oral and written communication through presentations and written reports. At the end of the semester, students participated in a survey to probe their perceptions about sustainability in MSE and their interest in jobs in related industries. In this article, we analyze student perceptions and self-evaluations to suggest improved methods of engaging students in sustainable materials design courses.

Introduction

Climate change has greatly impacted our global communities: causing more frequent and intense weather events, substantial damage to ecosystems, and increased challenges for food production and clean water availability [1]. The rate and magnitude of climate change impacts can be mitigated with urgent action to increase climate resiliency and drastically reduce greenhouse gas emissions. There is great need for sustainable development of our societies, which enables us to meet our present needs "without compromising the ability of future generations to meet their own needs" [2]. To achieve this, many industries must make changes to manufacturing and production methods in order to prioritize resource efficiency and reduction of emissions and waste, while meeting demands of an increasing consumption population.

In 2015, the United Nations adopted the "2030 Agenda for Sustainable Development", providing an ambitious plan to address global problems, including climate change, environmental health, poverty, and quality of life [3]. In this plan, the UN developed 17 Sustainable Development Goals (SDGs) to address the environmental, economic, and social dimensions of sustainable development, and provide an outline for specific objectives and targets for metrics of progress for achievement by 2030. Engineering is one of the fields that has been highlighted as integral in successfully achieving the SDGs [4], and as such, sustainability must be integrated into collegiate engineering curriculum to train the next generation of professionals to meet these goals and rise to the future challenges. The Accreditation Board for Engineering and Technology (ABET) validates these updates to curriculum with their student outcomes which highlight the importance of understanding and considering global and environmental context in engineering problems. Specifically, this is stated in Student Outcome 2 ("an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors") and Student Outcome 4 ("an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts")[5]. However, this emerging focus on sustainability poses a challenge to higher education institutions (HEIs). If engineers are expected to make large strides in addressing the SDGs by 2030, then HEIs need to increase focus in their degree programs to support these efforts [4]. This shift is not easily done; traditional engineering programs heavily focus on technical topics specifically related to the discipline of interest while sustainability and other ethical topics are often seen as secondary. These topics are minimally addressed in degree-specific courses and the burden is placed on general education courses for coverage [6]. The challenges HEIs face are further compounded by the need for highly multidisciplinary solutions for the SDGs. These multidisciplinary global challenges will require that the role of an engineer expands past traditional discipline-specific training [6].

Materials science and engineering (MSE) is widely regarded as a multidisciplinary field and is particularly relevant in addressing issues of sustainability. Materials engineers have direct impact on decision-making in industrial processes from product design, manufacturing, and disposal, and therefore MSE students are a prime focus group to integrate sustainability and other ethical and professional aspects into their education. The current generation of students is more aware of the need for sustainable engineering solutions than any generation before. This allows for the opportunity to increase student engagement in the classroom [7], [8]. By scaffolding new concepts to real world challenges and ideas, especially ones that students are already interested in, more engagement has been observed [9]–[11]. In order to advocate for sustainability concepts integrated in engineering education, graduates of MSE programs must possess fundamental materials knowledge in addition to understanding economic, social, and environmental drivers in design, manufacturing, and disposal in industrial practice. Therefore, including sustainability centered around UN SDGs within these curricula provides an excellent opportunity to educate and train ethical and socially-responsible engineers, which is the focus of our work.

Curriculum Considerations

At the University of Michigan, engineering curriculum includes broad understanding of the human, social, and environmental elements of engineering [12]. This entails developing systems-thinking skills, working on teams, and experiential learning. First year engineering students are exposed to these skills early on through an introductory engineering course, simulating a real-world engineering environment through team projects. These skills are built upon throughout the curriculum, particularly in required laboratory courses. In MSE, senior students take two semesters on engineering design as a core major requirement. The first senior capstone design course, "Sustainable Materials Design", has been restructured to focus on the economic, environmental, and social impact of engineering materials and processes through semester-long team projects. The objectives of the Sustainable Materials Design course are:

1. Identify and compare approaches to engineering design and the role of materials.
2. Apply engineering economic principles and understand their consideration in design projects.
3. Identify global sustainability problems and key technological challenges.
4. Use technical, economic, and ecologic information search procedures and implement collected information in engineering design.
5. Identify modern engineering and materials design procedures.
6. Implement methodology for analyzing the economic, environmental, and social impact in case studies and design projects.
7. Develop communication skills through written reports and oral presentations.
8. Discuss ethical, societal, and legal aspects in the engineering design context.

The overarching goal of the course is to provide a team environment in which each student can gain an understanding of key aspects of sustainability in materials development and engineering design, which fulfills ABET Student Outcomes 2, 3, 4 and 5 [5].

The course consists of collaborative team projects centered on global sustainability challenges as outlined by the UN SDGs to propose materials engineering solutions and examine the merit of the solution using relevant analysis methodologies. Students develop skills in communication through oral presentations and written reports at each stage of their project. Student teams first

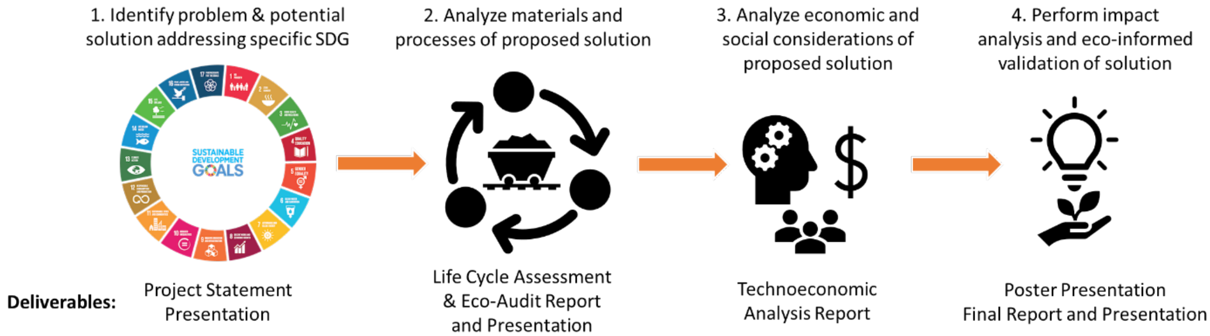

Figure 1: Team projects developed complexity throughout the semester, from (1) initial problem identification, (2) materials analysis, (3) economic and social analysis, and culminating in (4) a presentation of an eco-informed solution.

identify a materials engineering problem related to a specific SDG in which they are interested (**Fig 1-1**). As students are introduced to materials assessment methodologies, they apply these to their own projects. Teams use life cycle assessment (LCA) and eco-audits to analyze the environmental impact of their proposed solutions (**Fig 1-2**). The economics of their proposed solutions are examined through techno-economic analysis (TEA) (**Fig 1-3**). Finally, students take a holistic look at the ecological, economic, and social impacts of the problem and their proposed solutions and identify the tradeoffs driving the decision-making process (**Fig 1-4**). This course organization simultaneously grants students the freedom to engage in topics they are particularly interested in while delving deeply into the complexities of sustainable materials design.

Course Logistics

The course begins with an introduction to global sustainability challenges by examining the increasing consumption and demand for resources due to population growth and technological advances. This motivates the need for sustainable development and necessitates use of ecological and economic metrics to measure and compare progress. Students are then introduced to the UN Sustainable Development Goals as an anchor for their semester-long team projects where they will propose and analyze a solution to a specific problem. This provided context prepares students for developing their own interests into a team project, which increases engagement in the course content and improves course outcomes. Students are surveyed at the beginning of the semester to rank their interest in specific UN SDGs and other topics to inform the selection of teams (**Fig. 2**). Students have broad interests in many of the SDGs: 25% of the student

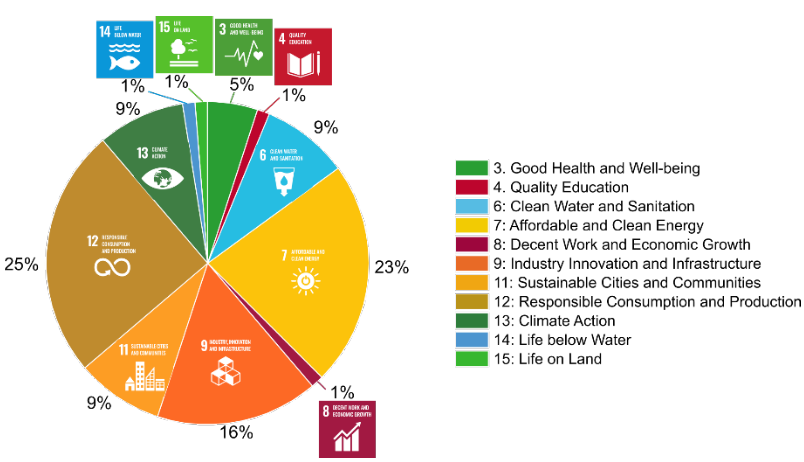

Figure 2: Students showed wide-ranging interest in the 11 of the 17 SDGs, with the greatest interest in 7, 9, and 12 due to the close connection of these goals to MSE content.

population indicated interest in SDG 12: Responsible Consumption and Production, 23% were interested in SDG 7: Affordable and Clean Energy, and 17% showed interest in SDG 9: Industry, Innovation, and Infrastructure. The high interest in these specific SDGs is likely due to which goals most closely relate to materials engineering topics at the intersection with other content covered in other MSE courses, such as batteries, renewable energy, structural and construction materials, and polymeric materials.

After the initial survey, students are then placed into teams of 4 or 5 peers based on their interests and availability to meet outside of class **(Fig 3)**. The survey and team placement were performed anonymously through CATME's team-maker tool [13]. The Fall 2021 semester had 45 students, and collectively had a wide variety of interests leading to greater variation of selected UN SDG focus. In the Fall 2022 semester with 43 students, many were interested in different aspects of SDG 12: Responsible Consumption and Production. This SDG encompasses waste reduction, waste management, and efficient use of resources which are greatly impacted by industrial materials production and manufacturing, enabling many relevant project topics in this course.

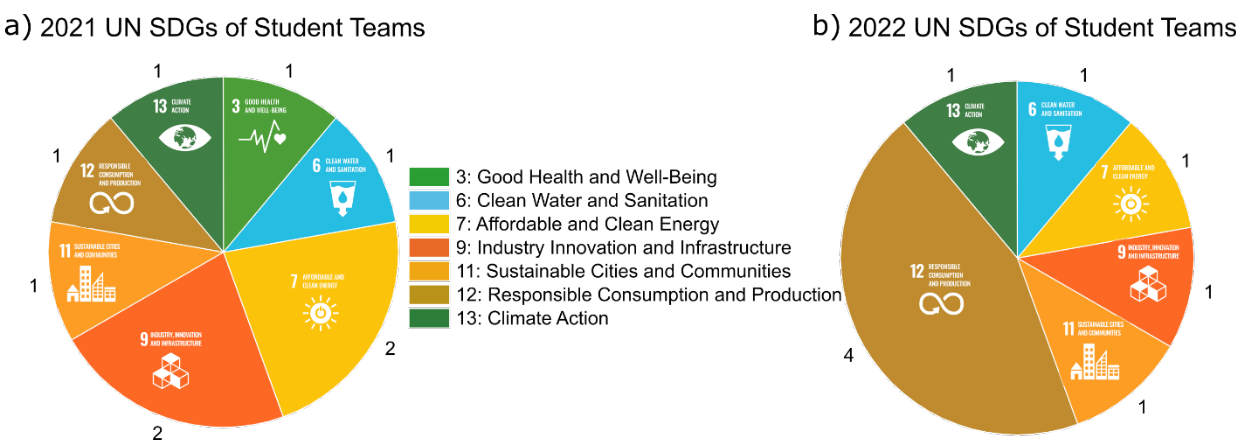

Figure 3: Selected UN SDGs of Student Teams. a) In 2021, 9 teams were formed around 7 SDGs. b) In 2022, 4 of 9 teams were interested in different aspects of SDG 12.

Initial Project Development

Once the teams were formed, students began researching their assigned SDG. Teams identified a specific technical challenge related to MSE and defined a preliminary project objective, identifying the core issue and its impacts and opportunities. The broad applicability of the SDGs allowed for unique projects to develop throughout the course, even between teams assigned the same SDG as seen in **Table 1**. After selecting project topics and completing preliminary research, students then presented their project statement to the class, with initial analysis of the potential impact of their objective, the strengths, weakness, opportunities, and threats (SWOT), and the potential stakeholders. This project development scaffolding enabled teams to approach design by first critically considering the needs within the context of their SDG.

Table 1: 2021 and 2022 Team Projects

2021		**2022**	
SDG	**Project Title**	**SDG**	**Project Title**
3 GOOD HEALTH AND WELL-BEING	Providing Accessible At-Home HIV Diagnostic Paper Tests	6 CLEAN WATER AND SANITATION	Sustainable Water Filtration Systems for Rural Ethiopia
6 CLEAN WATER AND SANITATION	Alternative Safe Solutions to Lead Pipes	7 AFFORDABLE AND CLEAN ENERGY	Solar Powered Desalination
7 AFFORDABLE AND CLEAN ENERGY	Sodium-Sulfur Batteries to Enable Sustainable Grid Energy Storage	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Miracle on Concrete: Carbon-Capture
7 AFFORDABLE AND CLEAN ENERGY	Renewable Photovoltaic Roofing for Electric Vehicle Implementation	11 SUSTAINABLE CITIES AND COMMUNITIES	Porous Concrete as a Solution for Potholes
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Aluminum Recycling for Lightweight Transportation	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	In-Home 3D Printer Filament Recycling Solution
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Reducing Net Carbon Emissions in Industry: Carbonizing Concrete	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Chemical Recycling for Fast Fashion Disposal Alternatives
11 SUSTAINABLE CITIES AND COMMUNITIES	Designing Porous Asphalt for Municipal Flood Mitigation	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Cornstarch-Based Packing Peanuts for Sustainable Packaging
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Recycling Bottles into rPET to Reduce Virgin PET Consumption	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Reducing CO_2 Emissions Via Active Carbon Capture
13 CLIMATE ACTION	Carbon Captured-Based Carbon Fiber Wind Turbine Blades	13 CLIMATE ACTION	Plastic Bottle Alternatives

Selection of Materials and Processes

In the second phase of the project, students were introduced to materials selection decision making, through case studies. Materials selection is determined by its function, the constraints that must be met, and the objective. Students are shown how optimizing multiple objectives includes analyzing the tradeoffs in material properties and ecological metrics like resource consumption, embodied energy, processing waste, carbon footprint, water consumption, cost, etc. Life cycle assessment and eco-properties analysis are examined as analytic methodologies to compare the impacts of materials and processing choices on ecological outcomes such as carbon emissions, water usage, and energy usage. Students applied these methodologies to their projects to analyze the environmental impact of materials and their processes. This provides an opportunity to introduce relevant software tools in the curriculum to further support the training of new graduates. We collaborated with Ansys, incorporating their Granta EduPack software into the course. Granta EduPack supports both materials selection and sustainability databases in the classroom, and is the educational version of Ansys Granta Selector, used for industry-level materials selection. This software enables students to easily compare the performance properties of materials and view the environmental impacts of choosing one material or process over another. Students used these data to create life cycle diagrams of their project scope, and generated LCA and eco-audit reports detailing these findings, which were presented to the class in written and oral presentation formats.

Techno-Economic and Social Analysis

After developing an understanding of how materials and processing selection can be assessed using ecological metrics, the economic and social variables were examined. The cost of technological development is a key decision variable that can be studied through techno-economic analysis (TEA). Teams applied TEA methodologies to their projects by diagraming the process of making or developing their solution, and identifying the relevant costs which may include raw materials, transportation, capital equipment, personnel, energy, etc. Teams were asked to make reasonable assumptions to breakdown the total costs of their proposed solution to determine the fixed and variable costs as a function of production volume and scale, and estimate the return on investment and a break-even point. Additionally, students examined relevant national and international legislation that impacted their projects. For example, students looking at alternative battery technologies found policies that financially incentivized the development of their products through subsidies. Other students found policies that taxed specific emissions. The TEA framework enabled students to examine how these policies impact the economic and environmental outcomes of engineering design. The teams then wrote detailed TEA reports, where they justified choices made in their solution based on the economic data. Additionally, students summarized how policy impacts the implementation of their solutions, making suggestions on opportunities for potential local and national legislative lobbying based on the social impacts of their work.

Reflection and Impact Analysis

In the final section of the course, teams are encouraged to revisit each analytic methodology and make improvements based on what they have learned over the semester. Students gather the data collected to assess the problem initially identified, consider the environmental, economic, and social impacts of their proposed design, and make final executive recommendations, noting the potential tradeoffs in the design. This cumulative work is presented in a final presentation and distilled into a poster presentation. These presentations allow for reflection on how the project has developed over the course of the semester, reiterating the importance of holistic consideration in design decision-making. Students have the opportunity to present their semester's work and improve their communication skills through an open poster session for the department, and received feedback from faculty, undergraduate and graduate students external to the course.

Student Feedback and Course Outcomes

This restructured Sustainable Materials Design course has been delivered for two years, with improvements in course content, structure, and assignments towards SDG-centered projects based on student feedback. Additionally, students were given a separate survey developed to measure the impacts of the course design in developing greater understanding of sustainability in materials science and engineering. The survey was developed in collaboration with our industry partner, and asked students to respond using a Likert scale of strongly disagree to strongly agree. This survey was reviewed by the Institutional Review Board (IRB) (HUM00228728) and was determined to be "not regulated". The survey data presented includes responses from 35 out of 43 students (81% response rate) in the Fall 2022 semester.

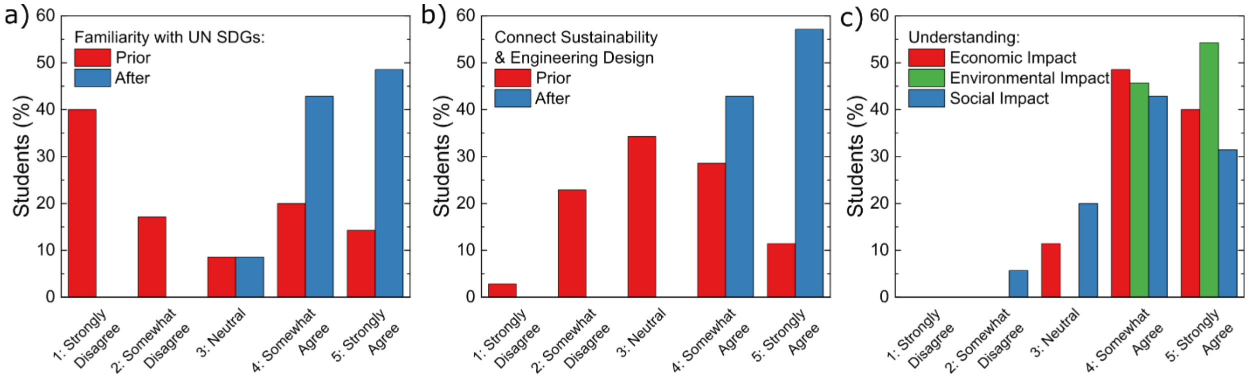

Figure 4: The course design (a) increased student familiarity with UN SDGs, (b) increased student's understanding of the connections between sustainability and engineering design, (c) leading to most students agreeing they have developed greater understanding of the economic, environmental, and social impact of materials engineering.

Using the UN SDGs as a lens to motivate the necessity for improved engineering design allowed students to develop greater understanding of economic, environmental, and social impacts of materials engineering (**Fig 4**). Student familiarity with the UN SDGs can be correlated to their understanding of the connection between sustainability and engineering design. Prior to the course, only 34% of the class was familiar with the UN SDGs (**Fig 4a**) and 40% were familiar with connecting sustainability and engineering design (**Fig 4b**). As a result of the course, 91% agreed they were knowledgeable about the UN SDGs and 100% agreed they understood how sustainability connects to engineering design. This can be further seen in **Figure 4c** in the high rates of students who agreed they have developed a better understanding of the economic, environmental, and social impacts of materials engineering (89%, 100%, and 74% respectively).

All the respondents agreed that it is important to learn about global sustainability problems in the context of Materials Science and Engineering (23% Somewhat Agree, 77% Strongly Agree). This highlights the importance of developing curriculum in higher education that supports student learning on sustainable practices relevant to engineering disciplines. Using the UN Sustainable Development Goals as an anchor to discuss the real-world challenges of sustainability is an effective method of engaging students to apply their knowledge to real world problems they care about. Providing students the ability to research project topics they are interested in allows them to develop the necessary technical skills at a higher level because they are self-motivated. 74% of students agreed that framing the team project around the UN SDGs was more engaging then being randomly assigned to a preselected project topic.

Competence in Key Technical Skills

Several of the course objectives are focused on the technical skills students will have developed at the end of this course. The students demonstrated these skills through the deliverables that were required at each phase of the project. The quality of work turned in at the end of the semester shows improvement and understanding of the sustainable design methodologies. In the after-course survey, students were asked to agree or disagree on their competency using specific technical skills before and after the course (**Fig 5**). Overall, a majority of students agree they

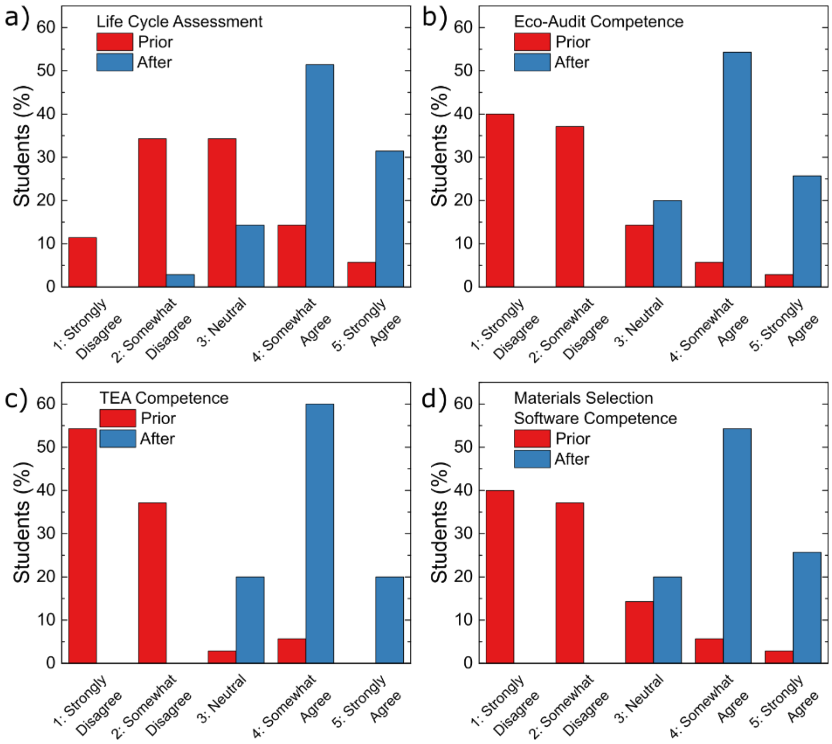

Figure 5: Students developed competencies in a) life cycle assessments, b) eco-audits, c) techno-economic analysis, and materials selection software.

have developed competency in performing LCA, eco-audits, TEA, and using materials selection software as a result of this course. Notably, very few students came into this course with prior understanding of these skills (LCA: 20%, eco-audit: 8%, TEA: 6%). Prior to the course, 9% of respondents were competent in materials selection software compared to 71% after the course. Similar improvements are seen in each of the other skills after the course (LCA: 83%, eco-audit: 80%, TEA: 80%). Additionally, 83% of students agree they are capable of searching and analyzing technical, economic, and ecologic information from materials databases and libraries. These data support the achievement of the course objective goals in developing technical skills. Students also indicate increased confidence in approaching and completing open-ended projects (91%). This course structure has prepared students with the technical skills necessary to enter the workforce and be successful in engineering design.

Career Impact

As a senior capstone course, one of the goals of the course was to introduce students to potential career paths through course content and guest lectures related to sustainability in engineering. Each semester of the course has featured several invited guests from academia and industry to share their work and how it relates to the SDGs (**Table 2**), as well as sharing their personal experiences and perspectives. The after-course survey inquired about the impacts of the course and the guest lectures on future career and educational pursuits. 77% of respondents expressed interested in furthering their education in sustainable engineering, and 71% want to incorporate sustainable engineering in their future career. Overall, the course content and the guest lectures increased student’s interest in

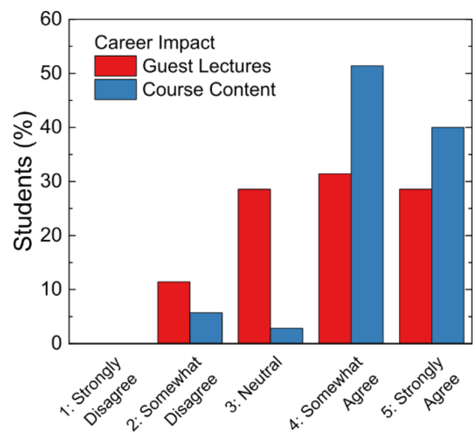

Figure 6: Guest lectures and course content increased interest in careers related to sustainable engineering.

pursuing a career in sustainable engineering (**Fig 6**). 60% of respondents agreed guest lectures increased interest, and 91% said course content increased career interest. Student comments also echoed this, sharing a desire for more guest lectures to be introduced to a wider variety of career pathways in sustainable materials.

Table 2: Invited Guest Lectures

Lecture Title	Guest lecturer	SDG
Unleashing the Potential of Biofabricated Cellulose for a Healthy Planet	Customer Engagement Coordinator from a Biotechnology Company	12
Workshop on Sustainable Materials Design - Ansys Granta EduPack	Education Team Representative from an Engineering Software Company	1, 4, 5, 7, 11, 12
Energy Materials from Agriculture Waste	Professor of Materials Science and Engineering	7
Naturally Derived Bioplastics from Shrimp and Squids: Processing, Fabrication, and Applications	Professor of Electrical Engineering and Co-founder of Biomaterials Start-up	9
How Nanoscale Interface Modifications Impact Macroscopic Sustainability: Two Stories of Water Technology	Professor of Mechanical Engineering and technical advisor of start-up company	6

Conclusions

To meet the rising challenges of climate change, undergraduate engineering education must incorporate sustainable design principles to prepare the next generation of engineers. Through a course framework anchored on the UN SDGs, the course content is able to progress through modern methodologies for assessing aspects of environmental, economic, and social parameters in order to optimize sustainable design. We have found that using the UN Sustainable Development Goals to contextualize design challenges is highly effective in motivating and engaging students in understanding sustainable engineering design. Creating teams of students with similar interests and allowing them to choose their own topics led to greater engagement and high-quality projects. Students achieve the course objectives and successfully demonstrate technical and communication skills as a result of the course structure. This work can easily be extended to other engineering fields because the UN SDGs broadly connect to many topics. Using real world problems and asking students to apply engineering concepts prepares them with the skills to approach, research, and make data-based recommendations on open-ended projects. This course structure also exposes students to career pathways in sustainable engineering through guest lecturers. Overall, this curriculum shift prepares students to consider and measure the environmental, economic, and social aspects of engineering when making design decisions, and should be replicated in other courses.

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