Pollution Prevention Through Popcorn: An Introduction to Life Cycle Analysis

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Abstract

Sustainable design thinking is essential in addressing environmental challenges, with Life Cycle Analysis (LCA) serving as a critical tool for evaluating resource efficiency, waste generation, and assessing environmental impacts of products and process. Despite its significance, LCA is rarely integrated into most educational curricula. An example is the k-12 curricula. To address this educational gap, we developed an outreach module that introduces LCA concepts through an accessible and engaging experiment involving a related food item, popcorn. This activity served as a foundation to introduce students to core chemical engineering principles and sustainability frameworks such as cradle-to-gate (raw material extraction to production) and cradle-to-grave (production through to end-of-life disposal). Four (4) popcorn popping methods; hot air popper, microwave, movie theater machine, and jiffy pop were analyzed assessing the different modes of heat transfer, energy and the materials used in each method. Students used Wattmeters to quantify the energy consumption of each method and conducted a streamlined LCA assessing metrics such as energy and mass consumption as well as sensory evaluation through taste. Thus, resulting in a comparative analysis of all four popcorn popping methods. This activity bridges the educational gap by linking theoretical concepts with real-world applications, fostering critical and sustainable thinking and promoting environmental awareness at an early stage.

1.0 Introduction

1.1 Life Cycle Analysis (LCA)

Life Cycle Analysis is a methodology used to assess the environmental impacts of a product or process throughout its entire life cycle, from raw material extraction to disposal [1], [2]. It consists of four main phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. In the goal and scope definition phase, the objectives of the study are set, including the boundaries of the system and the impact categories to be considered. This phase ensures that the study is aligned with sustainability goals, helping to identify areas for improvement. The inventory analysis phase involves gathering data on materials, energy inputs, emissions, and waste throughout the product's life cycle. This information is crucial for the impact assessment phase, where the environmental consequences of the product are quantified, such as its carbon footprint, water use, or toxicity. The final phase, interpretation, involves synthesizing the findings, addressing uncertainties, and providing recommendations for improvement. This phase helps ensure the results are relevant and actionable for decision-makers [3].

Generally, LCA can be performed using cradle-to-gate, cradle-to-grave, or cradle-to-cradle assessments [4], [5]. By evaluating environmental impacts systematically, LCA helps identify areas where resource use can be minimized, waste reduced, and improving the sustainability and greenness of processes [6]. Despite challenges such as data availability and methodological complexity, LCA remains an essential tool for promoting more sustainable practices and improving product life cycles, driving progress toward reducing environmental impacts. Several studies have explored the science behind popping popcorn. One example is a professional development module designed to investigate the mysteries of microwave popcorn and the technologies that enable the process [7]. Another area of study is the simulation of radioactive decay using popcorn [8]. In our study, students were exposed to the cradle-to-grave approach of the Life Cycle Analysis (LCA) when evaluating the sustainability of different popcorn popping methods. This approach examines a simplified streamline life cycle analysis, from the packaging of the products to usage, and then to disposal. Students evaluated not only energy consumption and waste produced during use but also the long-term impacts of packaging materials and disposal. For instance, microwave popcorn typically comes in single-use plastic bags that adds to landfill waste. Whereas the popcorn produced by hot air poppers came from a plastic container that held the kernels, which created less waste by utilizing reusable containers. By considering packaging to disposal, students gained a deeper understanding of how sustainability extends beyond immediate energy use to include packaging waste, recyclability, and end-of-life disposal. Hence, the objective of this study was to introduce students to LCA by creating an outreach initiative that simplifies a complex concept for better understanding.

1.2 Forever Chemicals

Forever chemicals, or per and polyfluoroalkyl substances (PFAS), are a group of synthetic chemicals known for their water, grease, and stain resistant properties [9]. These chemicals were widely used in consumer products like nonstick cookware, water-repellent fabrics, and food packaging materials, particularly in the mid-20th century [10]. However, their persistence in the environment has raised significant environmental and health concerns. PFAS do not break down easily, earning them the nickname "forever chemicals," and has been found to accumulate in water, soil, and living organisms [11]. Studies have linked PFAS exposure to various health issues, including cancer, liver damage, and immune system disruption [12], [13], [14]. PFAS are a significant form of pollution due to their durability and tendency to accumulate in ecosystems. Once released into the environment, these chemicals can persist for decades, contaminating water supplies, soil, and even air. The persistence of PFAS in the environment, combined with their potential for harm, makes them a growing concern for pollution control and waste management efforts.

The use of PFAS in common consumer products, such as microwave popcorn bags, contributes to material waste and energy waste. These bags, typically coated with PFAS to enhance grease and moisture resistance, are non-recyclable due to the inherent stability of the chemical [15]. Thus, contributing to the increased landfill accumulation. Traditional recycling systems are unable to process PFAS-coated materials such as microwave popcorn bags, rendering these bags unsuitable for reuse or repurposing. Currently, the FDA has proposed new legislation to prohibit the use of PFAS in food packaging [16]. However, there remains limited information regarding the materials used as coatings for paper bags in existing products. Consequently, the energy that could have been utilized for recycling is instead diverted, as the bags are landfilled or incinerated. These disposal methods not only demand additional energy but also contribute to environmental degradation. The inefficiency of managing PFAS waste highlights the broader issue of unsustainable product design and the importance of making choices that reduce both material and energy waste. Through our experiment, students are encouraged to consider both material and energy waste incorporating the LCA approach. By analyzing the environmental impacts of products like microwave popcorn bags, they learn how the inclusion of chemicals such as PFAS can complicate recycling, increase energy consumption in waste management, and contribute to long-term environmental harm. We engaged the students on forever chemicals through a just-in-time method at each of the popcorn popping stations. This comprehensive approach helps students understand the broader implications of their consumer choices and the importance of selecting products that minimize both material waste and energy waste, promoting sustainability.

2.0 Goal of the Experiment

2.1 School Curricula

LCA, despite its profound importance in understanding sustainability and waste reduction, is notably absent from most K-12 education. The New Jersey Student Learning Standards for Science [17] emphasize critical concepts like energy transfer, systems thinking, and designing evidence-based solutions, yet they do not explicitly incorporate the holistic framework of evaluating the environmental impacts of products and processes throughout their life cycles. This omission leaves a gap in students' education, particularly in equipping them with tools to critically assess the sustainability of consumer choices.

This activity was designed as a part of an outreach program during the summer of 2024 to expose K-12 students to engineering concepts. This activity is designed to bridge this educational gap, targeting middle and high school students who are developmentally ready to grasp the interconnected concepts of energy use, waste generation, and sustainability. However, this activity could be easily adjusted to target students of a younger age as well. The targeted age groups are particularly suited for this activity, as they are beginning to explore more complex systems and environmental issues in their science education. According to the current science curriculum for the state of New Jersey, the activity already aligns with the goals to emphasize systems design thinking and energy transfer by encouraging students to evaluate the entire life cycle of a product—from raw material extraction to disposal. This activity provides a hands-on and engaging approach using a relatable item, such as popcorn to introduce students to LCA, thus connecting abstract scientific principles to tangible, real-world applications.

In addition to addressing the gap in LCA education, this activity complements several key areas of current STEM education standards according to the Department of Education in the state of New Jersey. Specifically, standards under "Energy" (PS3) are discussed through the exploration of heat transfer principles—conduction, convection, and radiation—in the different popcorn popping techniques shown in the activity. The activity also aligns with "Engineering, Technology, and Applications of Science" (ETS1), the activity allows for the students to engage in problem-solving and evidence-based evaluations of various designs throughout participation. By measuring energy use, analyzing waste, and assessing the recyclability of materials, students practice essential scientific and engineering practices, such as analyzing and interpreting data, constructing explanations, and designing solutions. During the experiment the students also get an emphasis on crosscutting concepts like "Cause and Effect" and "Systems and System Models." Students are able to consider the broader implications of their findings on environmental systems through this activity. The use of familiar consumer products, such as microwaves, microwave popcorn bags and hot air poppers, and kitchenware such as frying pans foster relatable and meaningful discussions about sustainability, packaging materials, and energy efficiency.

By filling the gap in LCA education while building on existing curriculum goals, this activity provides middle and high school students with a comprehensive and enriching science experience. It empowers them to think critically about their consumer choices and equips them with the skills to analyze and address environmental challenges. This integration of LCA into science education is a vital step toward cultivating environmentally conscious citizens and inspiring the next generation of chemical engineers and sustainability advocates.

2.2 Methods of Popping Popcorn & Heat Transfer Principles

Four different methods were used to demonstrate the science of popping popcorn. The methods include a microwave, hot air popper, movie theater machine, and jiffy pop container over a stove. Each of these methods allowed for the ability to showcase the differences in waste accumulation and compare overall sustainability. The methods also demonstrated the three main heat transfer mechanisms: radiation, convection, and conduction. The microwave method demonstrates a way to heat the kernels using microwaves, which are electromagnetic waves at a frequency of 2.45 GHz obtained by dividing the speed of light by the wavelength that excites the dipole moment of the water molecules present within the kernels. As a result, this generates heat internally, causing the water to boil and the kernels to explode. This interaction results in internal generation of heat known as dielectric heating [18]. Radiation is a fundamental concept in heat transfer, as it shows how energy can be transferred without direct contact [18]. However, there are instances of uneven heat distribution due to the volumetric heating as the energy is specifically not uniformly directed to each kernel. This uneven heat distribution can further be explained by the nature of the microwave propagation, characterized by alternating peaks and valleys of the emitted electromagnetic waves. Maximum heating occurs at the antinodes, where energy intensity is highest, while minimal heating takes place at the nodes, where the energy intensity is significantly lower. This spatial variation in heat distribution within the microwave contributes to the inconsistent heating, resulting in variabilities in the popping process. Through this activity, students can easily visualize this invisible to the eye phenomenon, helping them grasp the idea of the action of microwaves heating popcorn.

The hot air popper showcases convection, where heated air passes around the kernels, transferring heat to the kernel surface and gradually heating the moisture inside. This continuous flow of air helps to ensure the kernels reach the temperatures needed to pop [19]. This method also helps to demonstrate the concept of heat transfer through a moving fluid (air), a critical principle in many industrial processes. Students can make the connection by having a real example of a process that is usually hard to see with the naked eye which can greatly help their understanding of these concepts. The final method using the movie theater machine and jiffy pop container illustrates conduction and convection, where heat travels directly from the stove top though the aluminum pan that holds the oil and kernels. This hot oil heats the shell of the kernel which intern heats the inside of the kernel until the moisture inside the kernels vaporizes causing the kernels to explode or pop. This method provides a hands-on demonstration of heat transfer through solid and liquid materials, an essential process in chemical engineering operations like heat exchangers. Teaching heat transfer principles, which are inherently abstract scientific concepts through methods of making popcorn that nearly all students have most likely used, significantly enhances understanding and fosters a deeper appreciation of chemical engineering principles within the educational setting.

3.0 Module Procedure

3.1 Materials

The materials used in this module include a hot air popper, a microwave, paper bags, paper towels, plain popcorn kernels, plastic bowls, large spoon, wattmeter, stovetop/burner, movie theater machine, and a Jiffy Pop® pan. The experiment involves using a hot air popper, microwave, theatre machine and stovetop/burner with a Jiffy Pop Pan® to pop popcorn. Plain popcorn kernels are used in the hot air popper and movie theater machine, while microwave popcorn bags are used in the microwave. Paper bags are also used to distribute the popcorn among students, and plastic bowls and a large spoon are used for serving the popcorn during sensory evaluation.

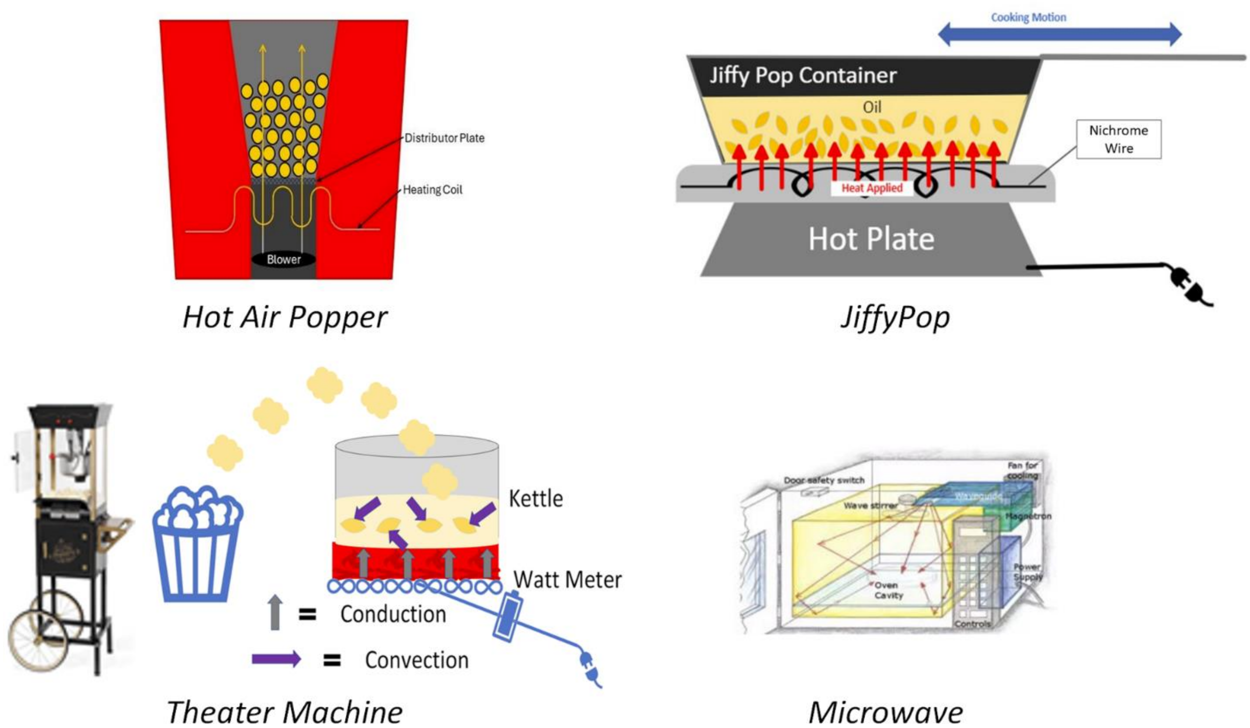

Figure 1: Popcorn Technologies

The wattmeter measures the energy consumption of each method, and paper towels are used for cleanup. Waste produced, including packaging and residual materials, are tracked for comparison, helping assess the mass and energy efficiency and environmental impact of each method.

The cost breakdown for the experiment is detailed in Table 1. The itemized cost breakdown is dependent on the total number of participants, hence the cost presented is for quantity required per group of students. For our activity, we did not have to purchase a microwave, the theatre machines as well as the Wattmeters since they were available to us for use at any time.

Table 1: Itemized cost breakdown for module

Item, Equipment	Quantity	Unit Cost, $
Microwave	1	180
Hot Air Popper[20]	1	33
Theatre Popcorn Machine[21]	1	71
Jiffy Pop[22]	1	13 (pack of 6)
Wattmeter[23]	4	45
Microwave Popcorn Bag[24]	1	37 (pack of 6)
Plastic Bowls[25]	1	10 (pack of 4)
Large Spoons/Spatula[26]	1	8 (pack of 4)
Paper Towel	1	0.68
Popcorn Bags[27]	1	10 (pack of 150)
Orville Popcorn Kernels[28]	1	7

3.2 Safety Considerations

Safety considerations were a key focus throughout the experiment, particularly with regard to burn hazards associated with the use of hot appliances and surfaces. The hot air popper, theatre machine and stovetop/burner with the jiffy pop pan involve the use of high heat, and students were instructed to handle these devices carefully, using oven mitts or heat-resistant gloves when necessary to avoid burns. The stovetop/burner was monitored closely to prevent overheating or accidental contact with hot surfaces, and students were cautioned about the risk of burns from both the burner itself and the jiffy pop pan. The microwave posed less of a burn risk but required attention to ensure that the microwave popcorn bags were handled carefully after heating, as they can become very hot. Paper towels were available to help with cleanup in case of spills or accidental burns. Overall, proper safety protocols were followed, including close supervision, appropriate protective gear, and clear instructions, ensuring that all students were able to participate safely in the module.

In addition to burn hazards, electrical hazards were a significant safety consideration, especially with the use of the hot air popper and microwave. Watt meters were also used to monitor energy consumption, and these devices were handled with care to avoid accidental contact with electrical components. The experiment emphasized the importance of ensuring that all appliances were properly plugged in and not overloaded. Any spills or wet surfaces were immediately cleaned up to prevent moisture from coming into contact with electrical appliances. Additionally, all students were educated on the proper procedure for turning off and unplugging appliances after use, and only authorized instructors assisted with electrical setup and troubleshooting. These safety measures minimized the risk of electric shock and ensured the safe use of electrical equipment during the experiment.

To prevent contamination of popcorn during the experiment, hygiene and handling protocols were implemented. Plastic bowls and large spoons used for serving the popcorn were cleaned and sanitized before each use, ensuring that no residues from previous tests would affect the quality of the popcorn. When handling the microwave popcorn bags or jiffy pop pan, students were reminded not to touch the popcorn directly, and any utensils that contained the popcorn were kept clean to avoid cross-contamination. Additionally, any spills or crumbs were immediately cleaned up to maintain a clean workspace and prevent contamination of other materials or the environment. All materials used in the module, including packaging, were checked for any damage or foreign contamination before being used, ensuring that the popcorn remained safe for sensory evaluation. By adhering to these hygiene practices, the risk of contamination was effectively minimized, allowing for accurate and safe tasting.

3.3 Experimental Procedure

The module was facelifted by both professors, undergrad, and graduate students who volunteered. This module begins with a 5 minute introductory talk with the students explaining the concepts of the module. Students were then given a pre-module survey to assess their initial understanding of sustainability, environmental issues, and the role of engineering in addressing these concerns. They were also asked to predict which method required more energy, with many students assuming that the larger machines, such as the movie theater popcorn machine, would use more energy. They could look at the rated wattage of the commercial devices to help with this assessment. After the survey, students performed an experiment comparing four popcorn-popping methods: a hot air popper, microwave, movie theater machine, and stove with jiffy pop. The students were divided into groups of 3-5 students, rotating through each of the 4 stations, with each group spending a total of 10 minutes at each station. Each method was chosen for its differences in energy use, waste production, and environmental impact.

During the module, students measured the energy consumption of each method using a wattmeter. They record the amount of energy used during the popping process and the time it takes for each method to complete the task in Watt hours which converts to joules of energy. They also track the mass of waste produced, including packaging such as microwave popcorn bags and aluminum containers from Jiffy Pop. This data helps them evaluate the environmental impact of each method. Next, students apply a streamlined LCA approach to assess the environmental impacts of each method. They compared the energy consumed, the waste produced, and the overall impact of each process. This helps students understand the sustainability of each method in a more systematic way. While waiting for the popcorn to pop, students learned about the heat transfer principles at play in each method as well as the mode of operation of each of the technologies used in the module. Understanding these heat transfer processes helps explain the energy consumption differences between the methods.

Once the data is gathered, students conduct a sensory evaluation, tasting the popcorn from each method. This allows them to compare the quality of the popcorn, such as taste and texture, while also considering the environmental trade-offs between different methods. After completing the module, students take a post-module survey to assess how their understanding of sustainability and environmental impacts has changed. By comparing the pre- and post-survey results, we were able to measure the effectiveness of the module in enhancing their knowledge of sustainability. Finally, students synthesize their findings from the LCA and sensory evaluations to determine which popcorn-popping method is the most sustainable. They consider factors such as energy use, waste production, and the taste of popcorn. The module concludes with a discussion on how the insights gained can apply to future engineering projects and the importance of making sustainable choices in design and technology.

The pre and post survey questions were designed to cater towards students from the large age range of K-12. To accommodate this simplified language was used in the development of the questions. The results from the pre- and post-module surveys played a critical role in quantifying how receptive students were to the content presented during the module. By asking questions about their awareness of energy consumption, waste production, and the environmental impact of everyday activities, we were able to capture a snapshot of their baseline knowledge and attitudes. After students completed the module, they took a post-module survey. This survey was structured to assess how their understanding had evolved after completing the module. The questions in the post-survey were like those in the pre-survey but also included questions designed to measure shifts in their knowledge and attitudes, such as their ability to evaluate the sustainability of various processes and their understanding of the importance of minimizing waste and energy consumption.

By comparing the responses from the pre- and post-surveys, we were able to quantify the degree of change in students' awareness and comprehension of sustainability. For example, if students showed a greater understanding of energy use, waste management, and the implications of different materials used in food packaging, this shift could be attributed to the content and activities covered in the module. The survey results not only provided insights into how much students learned but also highlighted which areas of sustainability and engineering the module helped them understand more deeply. In terms of receptiveness, the surveys helped us identify how engaged students were with the content. If students reported increased interest in sustainability or expressed more confidence in making environmentally conscious decisions, it indicated that they were responsive to the educational strategies and content. Additionally, the survey feedback provided valuable information about how well the module and discussions aligned with students' prior knowledge and interests. This information allowed us to assess the effectiveness of the module in fostering a deeper understanding of sustainability and environmental responsibility in an engaging, practical context.

4.0 Results

4.1 Comparative Analysis of Popcorn Popping Technologies

The results from the streamlined comparison between the different popcorn popping technologies regarding the mass and energy consumption scaled to the most mass and energy intensive technology is illustrated in Figure 2. The red line represents the energy consumption scaled to the most energy-intensive technology, while the green line indicates the mass consumption scaled to the highest mass-intensive technology.

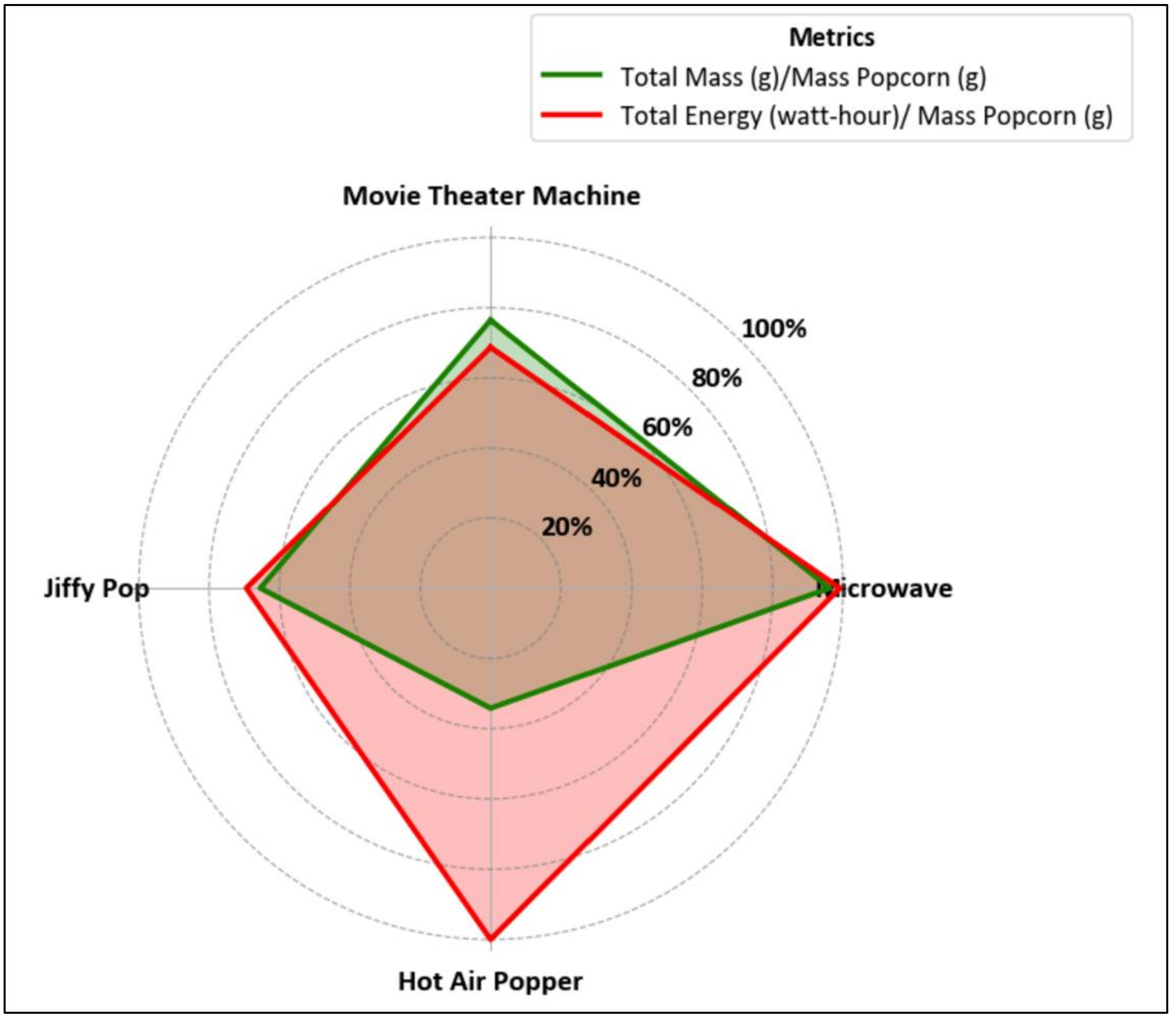

Figure 2: Radar plot comparison of mass (g/g of popcorn) and energy (watt-hour/g of popcorn) usage between popcorn popping technologies

For example, the hot air popper had the highest energy consumption so that was used to normalize, and the microwave bag used the highest amount of mass. The overall energy consumption per mass of popcorn between these technologies is also depicted in Figure 3. This bar chart shows that the hot air popper and the microwave technologies were the most energy intensive as compared to the theater machine and the jiffy pop.

The total mass accounted for in this study for all technologies relates to the packaging materials as well as the popcorn bags. The obtained total mass was scaled relative to the mass of the popcorn kernels used in each technology. Subsequently, the results were normalized against the worst-case scenario, defined by the technology with the highest mass intensity. As depicted in the radar plot in Figure 2, the microwave technology came up as the most mass intensive with the hot air popper being the less mass intensive technology. From the obtained results, we do observe differences in energy consumption across these various technologies employed in this module.

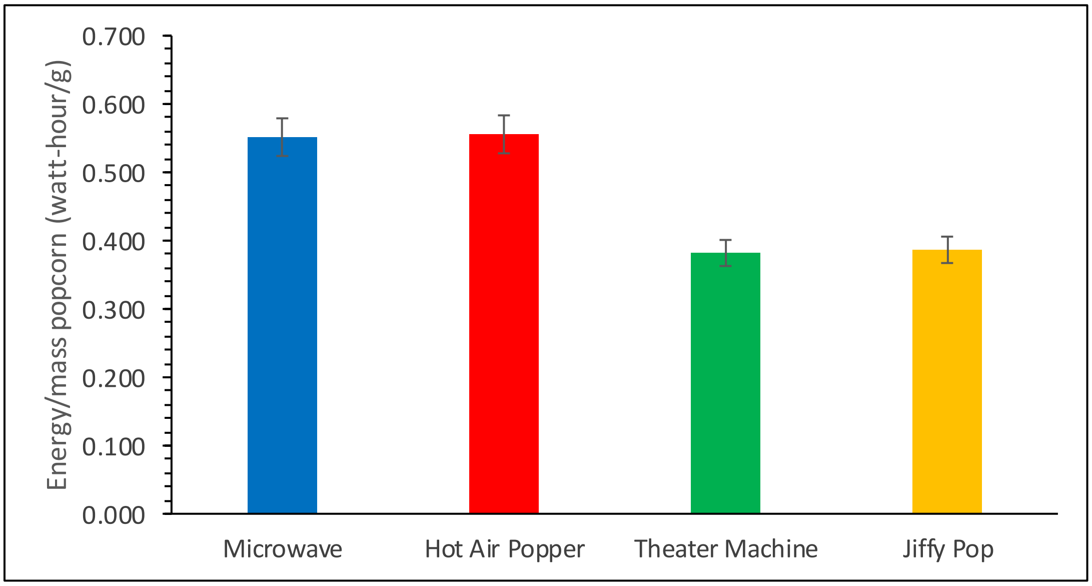

Figure 3: Comparison of energy consumption per mass of popcorn between the popcorn popping technologies

This can be attributed to heat transfer mechanisms, rates of heat transfer, and design features of each system. Specifically, the design plays a pivotal role, as it influences the available surface area for heat transfer, directly impacting energy consumption. Also, technologies that incorporate effective insulation and heat retention mechanisms demonstrate improved energy efficiency by minimizing the loss of heat to the environment.

The energy required to produce microwaves is higher than the energy required to heat up oil resulting in the observed high energy consumption from popping the kernels in the microwave. We did not actually estimate the energy required to heat up oil, but rather considered the energy usage measured with the wattmeter from the technology in heating. Unlike direct heating methods, such as stove-top cooking where heat is applied directly to the oils and kernels, a microwave first converts electrical energy into microwaves, exciting the water molecules in the kernels to generate heat. Hence, it results in the microwave process being more energy intensive.

The hot air popper on the other hand, operates in an open system, where heated air is used to boil the water molecules in the kernels which causes a rapid expansion of the kernel. This air only passes once through the device. Thus, it relies on convective heating mechanism for popping the kernels. This design results in energy being continuously lost by the heat content in the air flowing by the kernels and out to the surroundings. Hence, explaining its higher energy consumption just as the microwave compared to the other popping technologies. The theater machine and jiffy pop use conductive and convective modes of heat transfer, where heat is supplied in contact with a heated surface and also via liquid medium. Thus, these technologies as observed from the results have comparatively lower energy consumption as the direct contact with the heated surface and oil medium enhances the heat transfer, hence making these systems more energy efficient due to higher heat transfer coefficient. Conversely, the heat transfer through the air to the kernels in the hot air popper has a lower heat transfer coefficient, thus requiring more energy to drive the heating process. Thus, explain the higher energy usage associated with these technologies.

4.2 Impact Analysis

The activity was conducted with a total of 120 students over the span of the summer. As a result, the activity demonstrated a positive educational impact on the students, particularly in introducing them to the concept of Life Cycle Analysis. The questionnaires presented to the students seek to engage their thoughts on how the activity contributed to their understanding of LCA principles and whether it increased their interest in chemical engineering. The questionnaires were kept simple to accommodate the possibility of using diverse age groups covering all K-12 and ensuring relevance for both middle and high school students in the targeted audience. The survey questionnaires and results are illustrated in Figure 4. Survey results indicated that 57% of students had no prior knowledge of LCA before participating in the activity, highlighting its effectiveness in addressing a knowledge gap.

By the end of the session, 86% of the students indicated that the activity improved their comprehension of the concepts and importance of LCA, demonstrating its effectiveness in making complex sustainability topics accessible and comprehensible. The hands-on nature of the activity, which involved comparing different popcorn-making methods, allowed students to apply theoretical knowledge in a practical context, bridging abstract sustainability principles with real-world applications. However, 14% of the student body had a different perspective as they felt the module did not clearly help in their understanding of the concepts presented. The interactive design emphasized energy consumption, waste generation, and packaging implications, helping participants gain insights into environmental footprints.

Furthermore, the activity successfully engaged students and fostered an enjoyable learning experience. The survey findings revealed that 86% of students thought the activity was fun and engaging. The use of popcorn as a familiar and relatable subject matter effectively captured the attention of middle and high school students, making complex topics more approachable. Additionally, 85% of students (55% agree, 30% strongly agree) noted that the activity heightened their interest in chemical engineering and sustainability, aligning with the broader goal of encouraging students to explore STEM careers and sustainable practices.

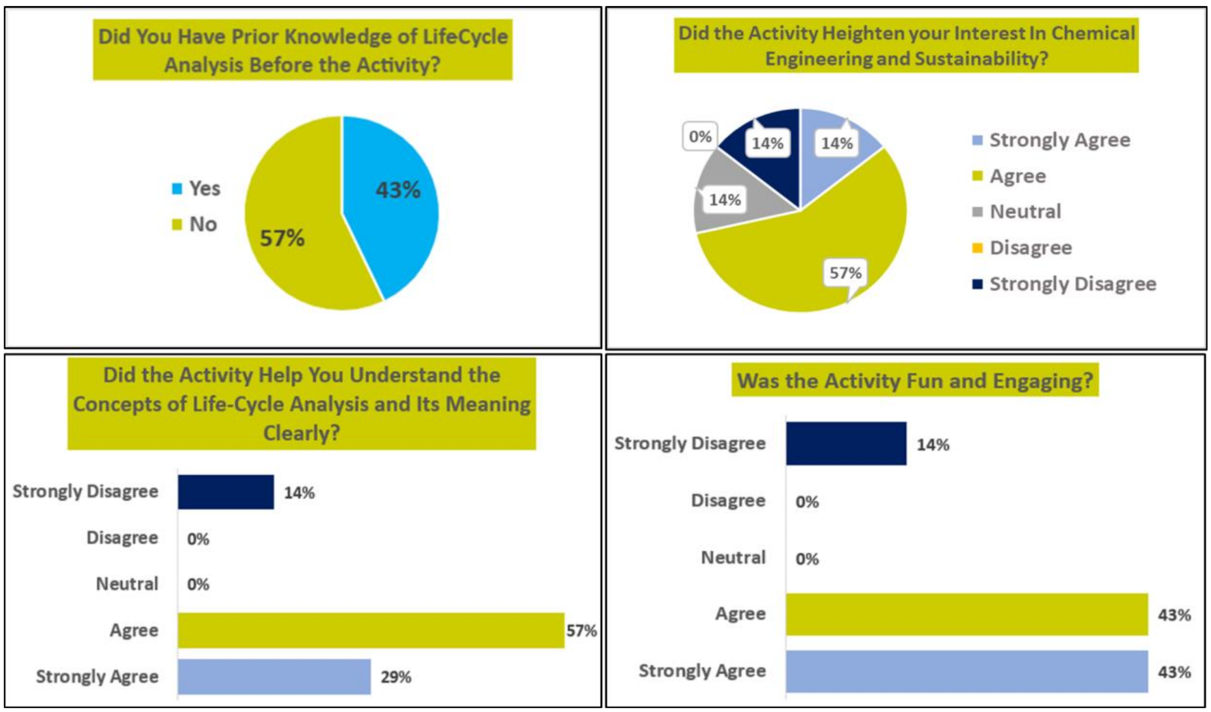

Figure 4: Pre-module and post-module survey questionnaire responses

In terms of behavioral and environmental awareness, the activity prompted students to critically evaluate consumer choices. By discussing single-use microwave popcorn bags versus reusable kernels and exploring PFAS contamination, participants connected everyday products to broader environmental issues. This approach fostered a comprehensive understanding of sustainability challenges. While the outreach activity was highly effective, some areas for improvement were identified. Feedback suggested expanding the activity to include additional case studies or exploring material sustainability and recycling practices in greater depth. Although the inclusion of taste as a metric made the activity engaging, placing greater emphasis on measurable sustainability criteria like energy efficiency and waste reduction could enhance its educational impact.

Overall, the activity successfully educated students about sustainability and LCA, sparking their interest in STEM and environmental issues. The positive survey results reflect its success in achieving its objectives. Moving forward, incorporating deeper analyses and stronger sustainability metrics could further enrich the activity's educational and environmental impact.

5.0 Conclusion

The activity introduced students to the concepts of pollution prevention and life cycle analysis (LCA) through the everyday example of popcorn-making. The activity highlighted the significance of sustainable practices, emphasizing topics not covered within the traditional school curricula. Four different popcorn popping technologies; the microwave, jiffy pop, theater machine, and hot air popper were assessed using a streamlined LCA approach to evaluate the mass and energy usage. By analyzing the science behind popcorn popping and comparing the amount of packaging and energy required in using these technologies, students gained insights into fundamental heat transfer principles and the broader implications of material and energy conservation. The activity further introduced students to the foundational concepts of chemical engineering, process optimization, heat transfer and energy conservation. Moreover, it underscored the importance of pollution prevention by focusing on selection of less toxic materials, waste reduction, and minimizing excess resources in processes. These principles aligned with green engineering and green chemistry, encouraging sustainable thinking.

By teaching these concepts to students, this activity helps bridge the gap between theory and practice and helps to instill in students a mindset oriented towards sustainability and safer choice decision making. This foundational knowledge equips them to integrate sustainability principles into diverse fields and everyday life.

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