Life Cycle Assessment as a Catalyst for Embedding Sustainability in Waste Management Practices

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Abstract: The establishment of sustainable campuses acts as a catalyst, fostering a Living Lab environment where active community engagement is crucial. Recognizing the pivotal role of waste management, university campuses prioritize detailed mapping and characterization of organic waste streams. This process paves the way for the identification of alternative scenarios that reduce and divert waste from landfills through valorization routes such as composting and anaerobic digestion. Acknowledging students' pivotal role in shaping sustainable solutions, their perceptions of solid waste separation assume significance. The effectiveness of the current separation system is critical, especially given the monitoring of bin contamination levels, revealing hindrances to organic waste valorization. Life Cycle Assessment (LCA) emerges as a valuable tool for identifying alternative scenarios for waste reduction and diversion, encompassing anaerobic digestion, composting, and waste-to-food strategies. This study centers on evaluating and reshaping student perspectives on organic waste separation and end-of-life waste management through LCA. A comprehensive survey was designed to elucidate current perspectives on the efficiency and communication of the existing waste management system. Student insights into waste separation practices revealed that the major barriers to effective waste management practices on campus include a lack of education and awareness regarding waste separation. The survey findings also underscore the significance of LCA not only in measuring carbon footprints but also in influencing perceptions and behaviors towards sustainable waste management practices. In conclusion, our study contributes to the discourse on embedding sustainability in educational settings, offering valuable insights for institutions aspiring to drive positive change through innovative waste management strategies.

Keywords: Waste Management, Sustainable development, Life cycle assessment

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Introduction

Industrialization growth and improved living standards have significantly increased waste production, adversely affecting the environment, contributing to climate change, and posing threats to wildlife, plants, and human health. Landfill waste decomposition releases methane, over 80 times more potent than carbon dioxide, while illegal burning emits substantial carbon dioxide, exacerbating global warming. Open landfills contribute to 91% of methane emissions, with approximately 40% of global waste disposed of in this manner (Gherhes et al., 2022). In response to these challenges, there is a significant emphasis on the circular economy, which underscores the importance of reducing, reusing, and recycling for economic prosperity and environmental well-being. This approach transforms waste into resources, holding considerable implications for the environment, economy, and society. The transition to a circular economy requires the adoption of zero-waste practices, promotion of environmental awareness, and prioritization of global sustainability. Achieving this shift relies on awareness and education initiatives that highlight the environmental impact of behaviors and instill values aligned with circular principles (Gherhes et al., 2022).

University campuses, as microcosms of cities, play a crucial role in reshaping dynamics and economies by leveraging knowledge to enhance management systems. Sustainable campuses can significantly improve overall city sustainability by serving as Living Labs. Illustrating effective municipal solid waste management and minimizing the environmental impact of food systems on campus can provide valuable models for local governments (Vergani, 2024). University campuses are not exempt from addressing the global environmental issue of food waste. Campus food waste contributes significantly to total community waste, offering universities an opportunity to reduce their carbon footprint and environmental impact. Consequently, many institutions prioritize implementing sustainable food systems, necessitating the design and implementation of innovative solutions to address this growing problem (Di Salvatore et al., 2022).

Therefore, this project is encompassed within an holistic approach that aims to implement a comprehensive living laboratory approach that improves the food systems at an university campus by mapping and characterizing the main streams of organic waste, evaluating waste separation efficiency, promoting sustainable food choices, exploring waste valorization strategies via waste-to-food and waste-to-energy perspectives, and conducting a life cycle assessment to evaluate environmental impacts. This study acts as a preliminary baseline determination for mapping the students perceptions regarding the waste management system of the campus. Their perceptions will be key for promoting an active participation of the campus community in the living lab approach. Moreover, we aim to test how integrating life cycle assessment (LCA) is crucial for evaluating impacts, products, and processes, providing a comprehensive understanding of complex systems like waste management in the campus. Specifically, this study aims to conduct a pilot outreach and education activity to engage the university community in sustainable food choices and waste reduction and diversion strategies and to reshape the students' perspective of waste source-separation through a LCA approach. This research seeks to understand students' knowledge regarding current environmental issues and their adoption of sustainable behaviors within a circular economy.

Method

This study was implemented in Tecnológico de Monterrey, which as part of its commitment to sustainability, has developed the Sustainability and Climate Change Plan for 2025. The plan aims to position the institution as a sustainability model, with goals including ensuring 100% of its campuses adopt sustainable waste management models and preventing 40% of waste from reaching landfills. Ultimately, the project will become replicable as a sustainable waste management model to other campuses, contribute to reducing greenhouse gas emissions, and benefit the university community and broader Ruta azul environmental goals. This pilot study involved students of 4th semester of Biotechnology Engineering who were asked to answer an open-ended survey aiming to catalyze reflection and catch the perceptions of the students regarding the current waste separation scheme in the campus. The students were not further instructed to avoid bias in their answers. Afterwards, they received a lecture on how the project aims to improve the waste management practices in the campus following several strategies, among which the communication of the environmental footprint of the source-separated waste streams is affected by the separation efficiency. Following this, they were introduced to LCA (Life Cycle Assessment) for evaluating the environmental sustainability of various approaches to reduce the environmental footprint of food systems. The students were then invited to share their thoughts on these subjects. After the session, once the instructor had addressed most of their questions and misconceptions, the students were given a survey to gauge their awareness levels and perceptions regarding waste separation.

Participants

The 4th semester students are part of the *Production of biotechnological products* course of the Biotechnology Engineering undergraduate program. This group was selected as the students were considered with enough knowledge to address a complex issue with a broader look and at the same time not have had a close approximation to the subject in other related courses. The group consisted of 7 boys, 12 girls, and 1 non-binary student. The students received instructions from both the main professor and an assistant professor on the present status of waste separation bins (and overall campus waste management), the living lab approach followed in the project, and methods for evaluating the sustainability of valorizing source-separated waste streams through an LCA methodology, and were encouraged to participate actively by expressing their opinions, in addition to completing a survey at the conclusion of the lecture. They were explicitly instructed to share their thoughts, with the assurance that there were no incorrect answers.

Open-Ended Survey Questions

This research seeks to understand students' knowledge regarding current environmental issues and their adoption of sustainable behaviors within a circular economy. The research questions were as follows:

Table 1. Questions of the open-ended survey applied to students.

Type	Question
A priori questionnaire	1. How would you describe the efficiency of the current waste management system on campus?
	2. If you are aware of end-of-life scenarios such as anaerobic digestion, composting, and waste-to-product transformation, could you share your knowledge on how proper waste separation contributes to these processes?
	3. In your opinion, is the waste in the separation containers appropriately diverted from landfill according to established recycling streams?
A posteriori questionnaire	4. How do you perceive the usefulness of the Life Cycle Analysis (LCA) Methodology as a tool to measure and achieve decarbonization objectives on campus? Do you believe that the LCA indicators allow for adequate measurement of the carbon footprint and are effective in guiding sustainability initiatives on campus?

The findings from the conducted survey were gathered and structured within a database for subsequent examination. Following this, a content analysis was undertaken to scrutinize the survey feedback, given the open-ended format of the questions. Our objective was to pinpoint prevalent themes, trends, and misunderstandings related to the waste management system on-campus by assigning them relevant keywords. This process involved categorizing the responses using Atlas.ti software. Additional qualitative analysis, including frequency assessment, was carried out to summarize the collective viewpoint of students on source-separation concerns and the adoption of LCA as a tool for sustainable development analysis.

Results and Discussion

According to a student survey, major barriers to effective waste management practices on campus include a lack of education and awareness regarding waste separation (Table 1). Many students expressed confusion about distinguishing between organic and inorganic waste, highlighting a need for clearer guidelines as the answers stated: *"Not everyone follows or knows how to separate their waste"* or *"I think they should educate students more about what is inorganic and organic because there is that confusion and sometimes you don't know where to put everything. That's why there are times when I see that there is plastic on the organic side"*. While some areas provide separate bins for different types of waste, this practice is not universal, further complicating the sorting process. Additionally, inconsistent participation from the university community contributes to the challenge, as one of the answers stated: *"I believe that there is a good intention for the separation of waste, however, students and staff sometimes do not take the task of carrying out such separations in the trash cans"*. Limited waste disposal options and a general lack of information exacerbate the problem, with some individuals resorting to tossing all waste in a single bin due to convenience: *"Many times not having all the garbage options*

makes people too lazy to look for the corresponding garbage can and they prefer to throw all the garbage in the same can". Addressing these barriers requires a multifaceted approach, including improved educational initiatives, consistent infrastructure, and efforts to incentivize proper waste disposal habits among the campus community. This is in line with the results of Owojori et al., (2022), who described that the major barriers to improving circularity at the University of Venda in South Africa were the students' lack of awareness and knowledge regarding practicability. One of the motivators reported by the authors is the establishment of education and awareness programs on waste management, which is similar to the main objective of the study, as we hypothesize that LCA methodology could further motivate the university community to engage in waste separation at source.

Table 1. Summary of question 1 answers

Major identified barriers
● Lack of education and awareness.
● Confusion over sorting
● Inconsistent waste separation practices
● Lack of participation
● Limited waste disposal options
● Insufficient information
Good points
● Adequate Distribution of Waste Containers
● Focus on Waste Separation
● Ease of Access to Recycling Bins
● University's Interest in Waste Management Initiatives
Opportunity areas
● Addition of containers for glass
● Enhancing the information of the location of specialized containers
● Inclusion of a container for cardboard
● Dissemination of information of waste management practices

According to the survey responses, several opportunity areas for improvement in our waste management practices have been identified (Figure 1). Firstly, respondents highlighted the absence of dedicated containers for glass waste, which poses a significant challenge as glass recycling is essential for sustainable waste management as one of the students said: *"I would think that the waste management system is sufficient, but it could improve since there are no containers that are for glass, and there are certain drinks available on campus which are based on this material"*.
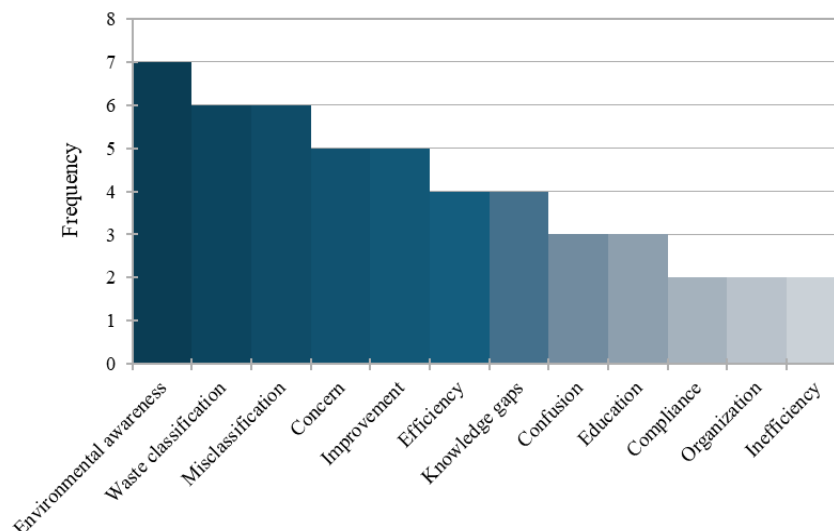

Figure 1. Frequency analysis of the categories identified in question 1.

Secondly, there is a pressing need for specific containers to handle hazardous materials such as sharp objects, laboratory waste and batteries: *"I consider that a specific trash can may be needed for sharp pulse materials, batteries and all that type of things, which, due to lack of them, end up being thrown in the trash cans"*. The

lack of proper disposal options for these items leads to improper disposal and potential environmental hazards. Also, while our waste sorting system is functional, respondents noted a noticeable gap in the absence of containers for cardboard recycling. Lastly, an opportunity for improvement in university waste management is the dissemination of information. Despite having sufficient waste containers focused on waste separation, there's a need to enhance how information is shared, another survey responses state: *"I think that there is a lack of more information for students to be able to correctly separate their waste, since I think that several students, including me, are not sure where they should be deposited"*. This could involve clearer signage, digital platforms, and educational materials across campus. Targeted outreach efforts like workshops and campaigns can further engage the university community, promoting sustainable behaviors and proper waste disposal.

The responses to question two highlight several key concepts which included waste management, waste classification, recycling, composting, and sustainability (Figure 2). Among the most notorious answers for this question were: *"These types of scenarios require specific waste to function, so I consider that properly separating the waste helps speed up the process more than anything, since it saves the step of manually separating the waste before moving on to the process that corresponds to the already be previously separated"* and *"waste classification separates components that can be degraded from the environment from those that cannot. Furthermore, this categorization of this last group can help facilitate a new use"*. This indicates that students consider it important to have appropriate waste management and classification. They believe that these practices have a direct impact on end-of-life scenarios such as anaerobic digestion, composting, and waste-to-product transformation. However, the answers also reveal a lack of knowledge regarding the anaerobic digestion scenario, as it is common to direct organic waste to composting or recycling. Only one of the answers mentioned the generation of byproducts such as biogas or biomass, which is related to anaerobic digestion: *"These processes have a positive impact on waste management, as they contribute to the use of waste to generate products such as biomass, biogas, etc. In order to reduce the environmental impact and take advantage of the circular economy"*. Recently, Flores-Nieves et al. (2022) reported the acceptance of anaerobic digestion by end-users as a waste management method and the use of biogas and biomass as energy suppliers and biofertilizers, respectively. It's crucial for students to understand the significance of anaerobic digestion in waste management, as it offers numerous benefits such as producing valuable byproducts. Familiarity with anaerobic digestion enhances their comprehension of holistic waste management practices and encourages more informed decision-making towards sustainable solutions.
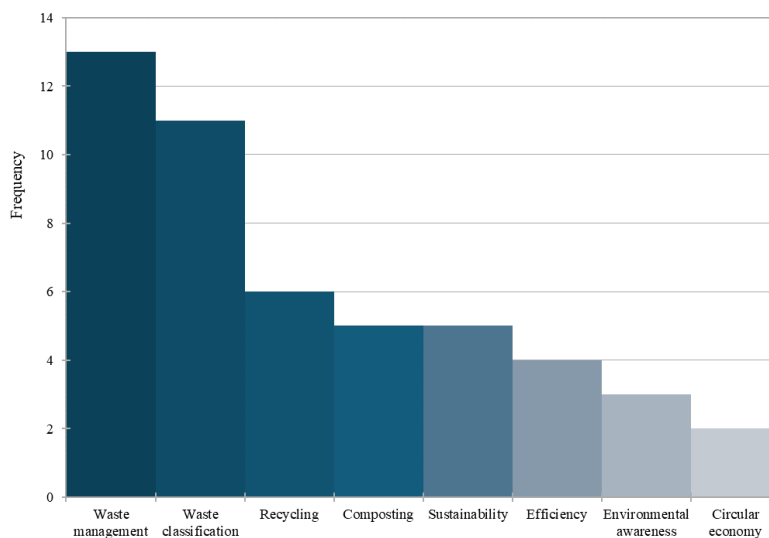

Figure 2. Frequency analysis of the categories identified in question 2.

Figure 3 depicts the frequency analysis of the categories identified in the students' responses to the question " *In your opinion, is the waste in the separation containers appropriately diverted from landfill according to established recycling streams?"*. The more frequent answer was the word uncertainty, followed by inefficient, effective, and behavior. Some respondents express doubt about whether waste separation is effectively implemented, citing reasons such as "*I don't know if the waste is correctly diverted to the landfill, but I think that this doesn't happen all the time. Before I saw that when they collected the waste from the containers, they mixed it*" or "*I consider that the waste is not being separated correctly, since not all students are aware of the separation that must be carried out. However, I am not sure if they are being taken to the correct landfills and I have not seen them being separated when collected*". Similar to the report by Amarachukwu et al. (2022), the

students reported that they don't have an idea of what happens to the waste generated in the University of Abuja, making it necessary to carry out extensive awareness programmes on waste management. Others express confidence in the waste separation process, believing that if handled correctly, waste can be diverted from landfill according to recycling streams. Overall, the responses highlight a need for improved education and awareness about waste separation practices, as well as greater transparency and accountability in waste management processes. It is evident that while efforts may be made to separate waste at the source, challenges remain in ensuring that waste is effectively diverted from landfill and recycled according to established streams. As Owojori et al. (2022) reported, the future studies could explore the potential of using various methods to spread awareness about sustainable practices. One avenue worth investigating is the integration of gamification into waste management and environmental education. By incorporating gaming elements, such as challenges and rewards, into these areas, there is the potential to foster a more positive connection between students and their surroundings. This approach not only encourages pro-environmental behavior but also enhances recycling efforts, providing institutions with an innovative tool to promote sustainability.
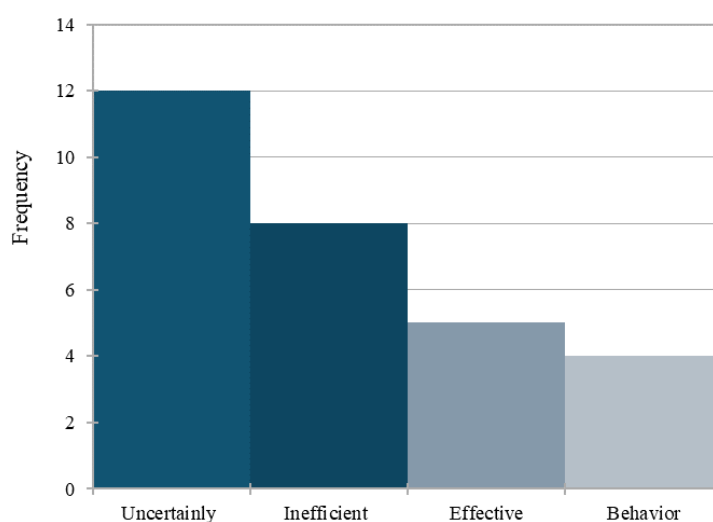

Figure 3. Frequency analysis of the categories identified in question 3.

Table 2 summarizes the key points of the student perspective regarding LCA methodology. Many respondents express confidence in the effectiveness and appropriateness of LCA methodology, considering it a valuable tool for guiding sustainability initiatives.

Table 2. Summary of question 4 answers

Key points
● Positive attitudes toward LCA methodology
● Awareness and education
● Scope for improvement
● Applicability to various areas
● Interest and impact
● Support for sustainability projects
● Effectiveness in measurement

 Some of the respondents stated "*I feel that this methodology is appropriate, since it allows us to raise awareness and inform about the carbonization of the campus*" or "*I believe that the LCA tool will achieve an adequate measurement of the carbon footprint and sustainability on campus*". Other students emphasized the use of this methodology in raising environmental awareness and consciousness, as well as educating students about their behavior and the sustainability of the university: "*I found the methodology very interesting and that it can help students think more about the environmental impact that their activities have on campus*" or "*I found the methodology very interesting and that it can help students think more about the environmental impact that their activities have on campus*".

The answers also showed the students are interested and understood the importance of LCA and suggested the application of this methodology for the impact evaluation of other products: "*Likewise, in the future it would be a good idea to apply it to other waste such as the use of cars, vapes*". A work developed by Johannisson and

Hiete (2021) reported the sensitivity of students to real-life problems using LCA. According to the authors, the LCA could improve the proactive learning strategies, such as problem-based learning, facilitating the development of strategic and practical competences in students, fostering critical and transdisciplinary skills essential for sustainability. They recognized the important role of this methodology to integrate the sustainable development goals into education and engineering (Figure 4).
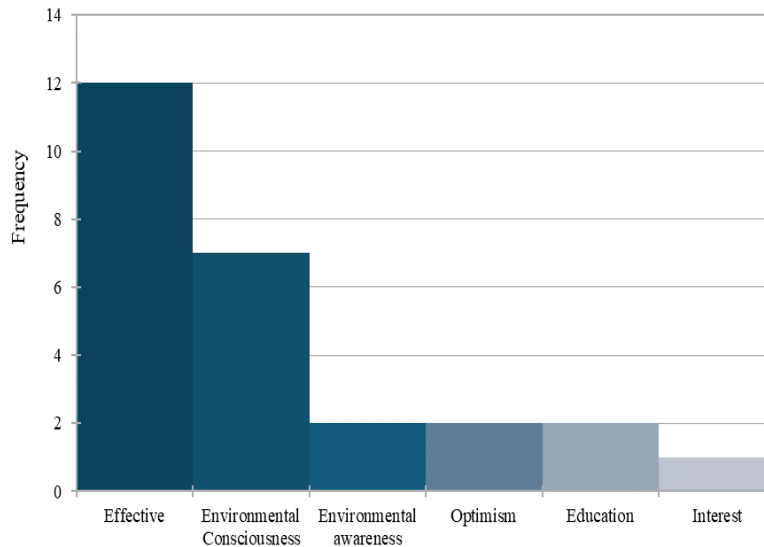

Figure 4. Frequency analysis of the categories identified in question 4.

Finally, Figure 5 presents a summary of the characteristic word cloud derived from the four responses. The size of each word corresponds to its frequency within the dataset. Notably, the most prevalent words include "*interest*" "*separation*", and "*effective*" Overall, the students demonstrate a notable level of concern and engagement regarding waste management practices.

Figure 5. Word cloud derived from the open-ended survey.

Particularly, they highlight the importance and effectiveness of waste separation, recognizing its potential impact on various end-of-life scenarios such as anaerobic digestion, composting, and waste-to-product transformation. This word cloud not only reflects academic discourse but also underscores the connection between academia and environmental action, encapsulating themes such as knowledge gap, environmental awareness, sustainability, and education. The knowledge gap highlights areas needing deeper understanding.

Surrounding it, environmental awareness fosters responsibility and stewardship. Sustainability embodies balanced futures, while education empowers change-makers.

Conclusion

This study provides valuable insights into the perceptions and challenges surrounding waste management practices on campus. The findings underscore the significant barriers posed by a lack of education and awareness, particularly regarding waste separation. To address these barriers, a multifaceted approach is required, needing for improved educational initiatives, consistent infrastructure, and efforts to incentivize proper waste disposal habits among the campus community. Moreover, the study identifies specific gaps in the existing waste management infrastructure, such as the absence of containers for cardboard recycling, highlighting the need for targeted improvements. Additionally, our research emphasizes the importance of enhanced information dissemination to promote understanding and engagement among students. Initiatives such as education and awareness programs on waste management emerge as significant motivators, aligning with the main objective of our study. Furthermore, the study underscores the importance of sustainable practices and the role of students in driving positive change within the campus community. Overall, our findings serve as a foundational baseline for future research and initiatives aimed at reshaping perspectives and fostering sustainable behaviors among students through innovative approaches such as LCA methodology.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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