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# Life Cycle Assessment of Microalgae-Based Domestic Wastewater Treatment and Biochar Production for Enhanced Sustainability

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## Abstract

While several studies have examined phycoremediation to treat domestic wastewater (DWW), a research gap persists on the environmental impacts associated with the resultant algal biomass. Hence, this study aims to assess the implications of microalgae-based systems for domestic wastewater treatment and biochar production for further applications using the Life Cycle Assessment (LCA) approach. Particularly, two systems were investigated: 1) an algal-based system treating DWW, and 2) another system for biochar production from microalgae grown in the selected wastewater. LCA boundary involved inputs (energy, DWW, and chemicals), and outputs (treated effluent, algal biomass, and biochar). Results showed that the scenario producing biochar showed the best results in the most impactful and stakeholder categories. This was primarily attributed to: i) the system simplicity, which consequently leads to an improvement in the health and safety concerns of workers; ii) the elimination of pollutants enhances health and safety, acceptableness, and odor effects for customers and the regional population; iii) the existence of robust laws, regulatory frameworks, and comprehensive implementation, which advantage value chain participants and society. These outcomes underscore the potential of integrated microalgae-biochar systems as a sustainable strategy for resource recovery, demonstrating significant reductions in environmental impacts across LCA categories. The study provides critical insights into scalable green technologies for wastewater valorization while mitigating ecological burdens.

### Keywords

Life Cycle Assessment; Phycoremediation; Environmental impacts; Wastewater valorization; Biochar

# 1. Introduction

Life cycle assessment (LCA) is an analytical tool employed to investigate the environmental impacts of any production processes [1]. According to the current rank and position of the keyword "life cycle," LCA is becoming more prevalent in the field of algal research. Four phases comprise an LCA, as defined by the International commission for Standardization (ISO) guidelines for conducting LCA (series; ISO 14040 and 14044): (i) goal and scope definition, (ii) life cycle inventory (LCI) analysis, (iii) life cycle impact assessment (LCIA), and (iv) life cycle interpretation [2]. LCA serves as a comprehensive decision-making tool to quantify the environmental, social, and economic impacts of diverse processes, feedstocks, and integrated strategies [3]. However, due to the extensive variability in results, it is infeasible to make generalized assertions regarding the role of LCA in algal biorefinery [4].

Microalgae are tiny organisms that can convert nutrients, carbon dioxide, and light into biomass rich with lipids, proteins, and carbohydrates in brief timeframes. The carbohydrate content of microalgae can be converted into biofuels like butanol and ethanol. In contrast, the lipid content can be used to make valuable byproducts like β-carotene and astaxanthin, which are used in the cosmetics industry. For several microalgae with low lipid content, pyrolysis may be a viable method to produce valuable compounds such as syngas, bio-oils, and bio-char [2].

Regarding their easy production techniques, microalgae are experienced as a possible alternative feedstock. Among the diverse candidates of photosynthetic organisms, microalgae have always garnered significant global interest due to their considerable benefits over terrestrial plants [5]. Microalgae, in contrast to conventional edible crops, are devoid of ethical concerns in their applications as they do not require arable land, necessitate significantly less cultivation area, approximately 49 to 132 times less than agricultural feedstock, and are not involved in 'food versus fuel' controversies. Consequently, microalgae represent attractive candidates for renewable energy generation and have a role in mitigating the effects of climate change and global warming [2]. Additionally, unlike traditional agriculture, microalgae are able to endure extreme environmental conditions such as wastewater [6]. Furthermore, the microalgal high proliferation rate for year-round [5] with doubling time ranging from 24 to 13 h [6] facilitates yielding the targeted products throughout all seasons [5]. This rapid growth also guarantees higher $CO_2$ fixation, mitigating the adverse impact of the global warming crisis. Generally, 1.83 kg of $CO_2$ can be absorbed by each kg of algal biomass [2]. In addition to $CO_2$ fixation, the ability to tuptake nutrients including ammonia ions ($NH_4^+$), nitrate ions ($NO_3^-$), and phosphate anions ($PO_4^-$) from wastewater makes microalgae potential wastewater purifiers [6].

In this context, the main objective of this work is to evaluate the impact categories (midpoint and endpoint) of LCA associated with the two studied scenarios (a) phycoremediation followed by land-filling of harvested biomass, and (b) phycoremediation followed by biomass valorization through pyrolysis.

# 2. Methodology

## 2.1. Goal, scope, and system boundaries

The objective of the LCA was to evaluate the environmental categories linked to the utilization of microalgae for wastewater treatment by integrating experimental and literature data into OpenLCA software (version 2.1.0). The boundaries of the two suggested scenarios encompassed pump operation, pollution elimination, depleted biomass regeneration, energy consumption, transportation, and pyrolysis. All laboratory-scale and literature data have been converted to a functional unit (FU) of 1 $m^3$ of wastewater for a valid comparison of the life cycle assessment (LCA) results of the two scenarios.

## 2.2. Life cycle inventory (LCI)

The life cycle inventory (LCI) approach was established for each phase, namely phycoremediation, landfilling, and pyrolysis. Experimental data collected on a laboratory scale was used to derive input and output observations. All calculations have been conducted following Morish et al. [7].

## 2.3. Life cycle impact assessment (LCIA)

The midpoint impact indicators included eutrophication, climate change, human toxicity, energy resources, and ecotoxicity. While the endpoint impact indicators encompassed human health, natural resources, and ecosystem quality.

## 3. Results & Discussion

Fig. 1 displays the consequences on the LCA environmental impact categories of different stages (phycoremediation, landfilling, and pyrolysis) for both cases. For instance, the phycoremediation step could enhance the quality of wastewater by reducing various pollutants, such as chemical oxygen demand (COD) and Nitrogen (N). This effluent release into the surroundings may mitigate the pollution effects on freshwater, terrestrial, and marine ecosystems. The discharge of pre-treated effluent into water bodies may pose health risks to humans, encompassing both carcinogenic and non-carcinogenic categories. Furthermore, the issue of eutrophication (marine and freshwater eutrophication potential) may lead to algal growth, which results in oxygen deficiency upon their death and decomposition [8].

Additionally, it was noted that the landfilling phase was the primary source of environmental impacts. For instance, this landfill discarding method demonstrated elevated greenhouse gases (GHG) emissions (0.02 kg $CO_2$ eq for the Climate Change) associated with $CH_4$ releases into the surroundings, resulting from anaerobic biological decomposition, which produces digestate and gases byproducts. Global warming capability related to methane's is 23-fold greater than that of an equivalent volume of carbon dioxide [9], rendering it a major contributor to climate change and global warming. Disadvantageous chemicals in landfill leachate may migrate to soil, negatively affecting the terrestrial ecotoxicity potential. For example, ammonia nitrogen molecules can degrade buildings, water bodies, and crops because they affect surrounding acidity (terrestrial acidification potential) [10].

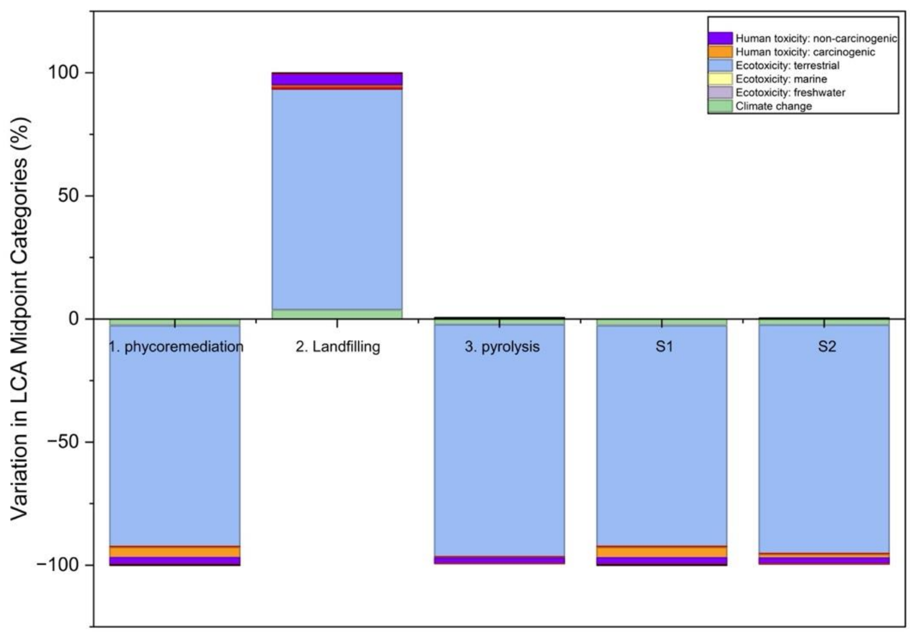


Fig. 1. Process contribution (midpoint) to life cycle environmental impacts of the both evaluated scenarios: Scenario_1: Phycoremediation and Landfilling, and Scenario_2: Phycoremediation and Landfilling.

The incorporation of the drying/pyrolysis phase for algal biomass valorization could mitigate many environmental problems associated with landfilling. Biochar produced from the thermal processing of depleted biomass may sequester greenhouse gases, primarily CO2, from the atmosphere, due to its significant carbon capture and storage capability.

Using biochar as a biofertilizer could help alleviate or perhaps eliminate some of the environmental impacts during the phytoremediation stage. The incorporation of algal biochar resulted in improvements in the growth and physiology of maize [11]. Thus, manufacturing chemical fertilizers and their final release into the agricultural drainage water would decrease. Hence, reducing the negative impact on human health and freshwater, marine, and terrestrial ecosystems.

All the categories in (Scen 1) and (Scen 2) exhibited a negative magnitude, indicating environmental advantages. Consequently, it could be concluded that the two studied scenarios showed positive results in terms of the valuable environmental midpoint categories.

Throughout the landfilling phase, all endpoint categories, namely ecosystem quality, human health, and natural resources, exhibited an environmental load (Fig. 2). This could be attributed to the release of methane and carbon dioxide gases, generated from oxygen-free decomposition processes, into the air. The inhalation of such gases by the human body could cause diseases including colon cancer. Additionally, these emissions from landfills may potentially exacerbate global warming, leading to the extinction of terrestrial species, including flora and fauna. Moreover, the diesel fuel necessary for transporting the depleted macrophytes to landfills may deplete existing fossil energy resources, exacerbating the issue of energy scarcity.

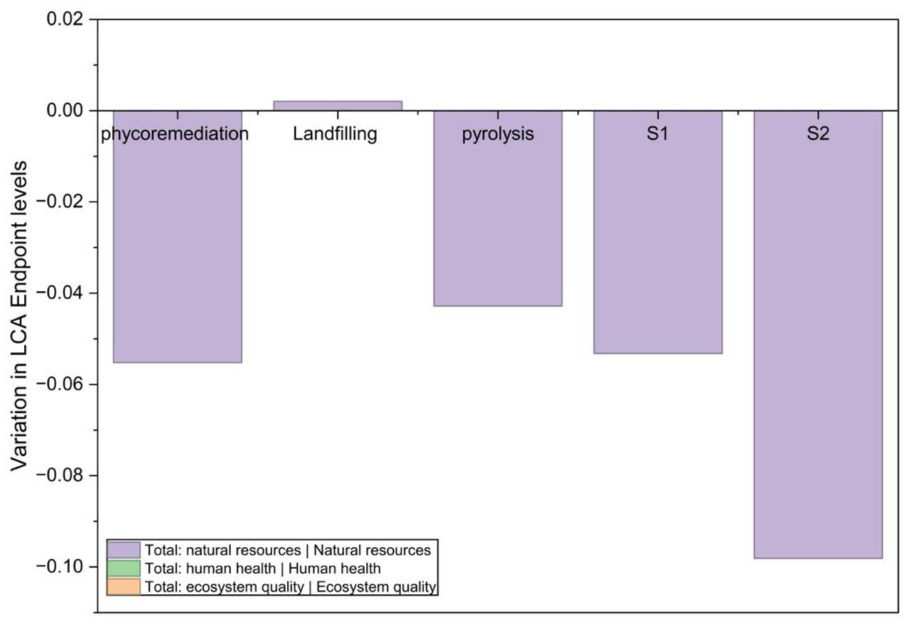


Fig. 2. Process contribution (endpoint) to life cycle environmental impacts of the two evaluated scenarios: Scenario_1: Phycoremediation and Landfilling, and Scenario_2: Phycoremediation and Biochar production.

## 4. Conclusion

This work uses Life Cycle Assessment (LCA) to demonstrate microalgae-based wastewater treatment and biochar synthesis systems for future use. Two systems were studied: an algal-based WW treatment system and a biochar manufacturing system from microalgae grown in the wastewater. Energy, WW, and chemicals were inputs, and treated effluent, algal biomass, and biochar were outputs. Both scenarios yielded good results in most impacts. These findings illuminate sustainable and affordable microalgal biomass recovery and biochar manufacturing systems. This study showed reduced environmental impacts from resource recovery life cycle assessment (LCA) impact categories.


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## References


[1] S. Mishra, M. Roy, and K. Mohanty, "Microalgal bioenergy production under zero-waste biorefinery approach: Recent advances and future perspectives," *Bioresource Technology*, vol. 292, p. 122008, 2019/11/01/ 2019, doi: https://doi.org/10.1016/j.biortech.2019.122008.

[2] W. Wu and J.-S. Chang, "Integrated algal biorefineries from process systems engineering aspects: A review," *Bioresource Technology*, vol. 291, p. 121939, 2019/11/01/ 2019, doi: https://doi.org/10.1016/j.biortech.2019.121939.

[3] M. Borzęcka-Walker, A. Faber, R. Pudełko, J. Kozyra, A. Syp, and R. Borek, "Life cycle assessment (LCA) of crops for energy production," *Journal of Food, Agriculture & Environment*, vol. 9, no. 3&4, pp. 698-700, 2011.

[4] M. Kashyap, S. Chakraborty, A. Kumari, A. Rai, S. Varjani, and V. Vinayak, "Strategies and challenges to enhance commercial viability of algal biorefineries for biofuel production," *Bioresource Technology*, vol. 387, p. 129551, 2023/11/01/ 2023, doi: https://doi.org/10.1016/j.biortech.2023.129551.

[5] H. I. Choi, S.-W. Hwang, and S. J. Sim, "Comprehensive approach to improving life-cycle CO2 reduction efficiency of microalgal biorefineries: A review," *Bioresource Technology*, vol. 291, p. 121879, 2019/11/01/ 2019, doi: https://doi.org/10.1016/j.biortech.2019.121879.

[6] K. S. Khoo *et al.*, "Recent advances in downstream processing of microalgae lipid recovery for biofuel production," *Bioresource Technology*, vol. 304, p. 122996, 2020/05/01/ 2020, doi: https://doi.org/10.1016/j.biortech.2020.122996.

[7] M. Azabo, A. Abdelhaleem, and M. Nasr, "Feasibility of phytoremediation/pyrolysis/adsorption framework for valorization of water hyacinth: Life cycle assessment, techno-economics, and sustainability pillars," *Journal of Water Process Engineering*, vol. 71, p. 107146, 2025/03/01/ 2025, doi: https://doi.org/10.1016/j.jwpe.2025.107146.

[8] S. Anang, M. Nasr, M. Fujii, and M. G. Ibrahim, "Synergism of Life Cycle Assessment and Sustainable Development Goals Techniques to Evaluate Downflow Hanging Sponge System Treating Low-Carbon Wastewater," *Sustainability*, vol. 16, no. 5, doi: 10.3390/su16052035.

[9] Y. Sun, G. Xu, Y. Wang, W. Shi, Y. Yu, and H. He, "In Situ Synthesis of Encapsulated Pd@silicalite-2 for Highly Stable Methane Catalytic Combustion," *Environmental Science & Technology*, vol. 57, no. 48, pp. 20370-20379, 2023/12/05 2023, doi: 10.1021/acs.est.3c05634.

[10] A. S. Ouedraogo, R. S. Frazier, and A. Kumar, "Comparative Life Cycle Assessment of Gasification and Landfilling for Disposal of Municipal Solid Wastes," *Energies*, vol. 14, no. 21, doi: 10.3390/en14217032.

[11] N. Ullah *et al.*, "Integrated Effect of Algal Biochar and Plant Growth Promoting Rhizobacteria on Physiology and Growth of Maize Under Deficit Irrigations," *Journal of Soil Science and Plant Nutrition*, vol. 20, no. 2, pp. 346-356, 2020/06/01 2020, doi: 10.1007/s42729-019-00112-0.