Algaenious Labs

Microalgae Biorefinery LCA

Sam Bookbinder, James Boyd, Vinya Nadimpalli, Annie Wang

BEST 402: Industrial Ecology

Dr. Qingshi Tu

December 18, 2023

Table of Contents

GRAPHICAL ABSTRACT **1**

ABSTRACT **1**

INTRODUCTION **2**

METHODOLOGY **4**

Model Structure and bounds: 4

1: Lipid Extraction: *4*

2: Protein Extraction: *7*

3: Ethanol Production: *8*

Algaenious Labs' single multi-step process 11

Conducting the LCA for Algaenious Labs 11

Determining the Carbon Footprint of Corn as a Feedstock 12

Assumptions 13

Algae composition: *13*

Solvent: *13*

Energy: *13*

Producing protein, ethanol, and lipid from corn *13*

LCA RESULTS & DISCUSSION **14**

Global Warming Potential 15

Comparison and Importance 16

Sensitivity Analysis 17

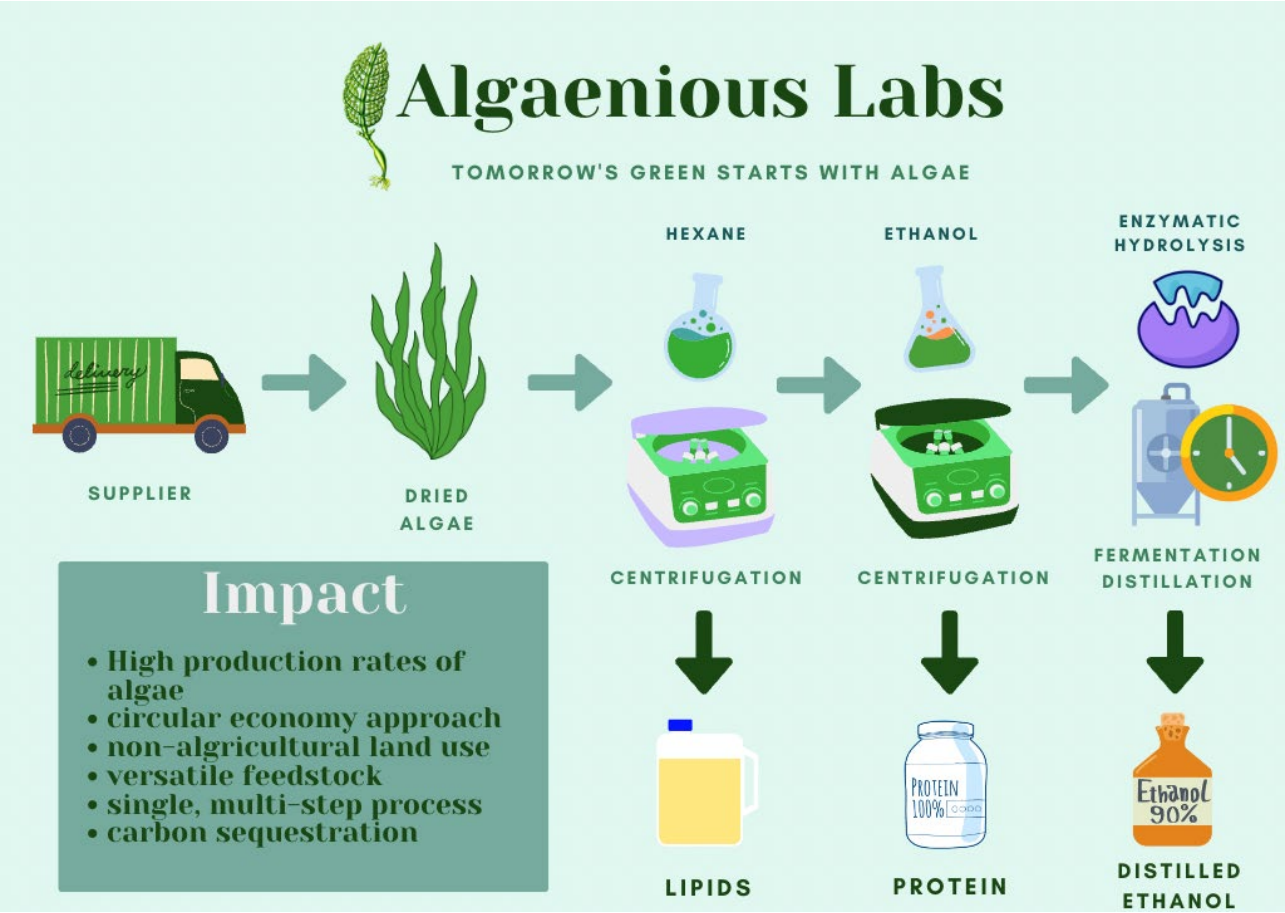
Limitations 18

CONCLUSION **19**

CONTRIBUTION STATEMENT **21**

REFERENCES **22**

Graphical Abstract



Abstract

Increasing pressure on resource availability due to a growing world population and climate change has raised concerns over the durability and sustainability of current production pathways, calling for urgent climate action. The pressing need to transition away from conventional production pathways is becoming more prevalent in order to reach ambitious climate goals. Algae has proven to be a promising candidate because of its ability to grow in low-quality water sources, its fast reproduction rate, and its high protein, lipid and ethanol

concentration. A startup called Algaenious Labs unleashes the potential of algae to produce lipids, ethanol and protein. The OpenLCA Life cycle assessment conducted in this report will reveal the carbon footprint of Algaenious Labs using algae as an alternate feedstock. The report will compare the carbon footprint of using alternate feedstocks such as corn and algae produced from Algaenious Labs in hopes of facilitating deducing the sustainable alternative source to produce ethanol, lipids and protein in the transition to a cleaner and greener world

Keywords – Algae, Microalgae, Biorefinery, LCA, Lipids, Proteins, Ethanol

Introduction

As our globe continues to cope with a rapidly growing world population, the pressure on resource availability combined with the dangers of climate change has highlighted the need for climate action and a transition to sustainable production practices. The growing urgency to adopt alternative production pathways with a lower carbon footprint is becoming more critical as we try to meet increasing global demand and meet global climate targets. Three essential compounds that make up most of our daily products include ethanol, lipids and proteins.

These essential compounds shape our daily needs and are a significant component in several products, ranging from food and beverages, cosmetics, medical components, biofuels and more. As the global population is projected to increase to 9.7 billion, the demand is only expected to grow, urging industries to re-evaluate their current production practices and reinvent pathways of lower carbon impact while maximizing output.

A potential candidate that researchers have turned their attention to is algae. The many kinds of microalgae serve as a promising substitute to current feedstocks as a source of lipids, ethanol, and proteins. Its rapid reproduction rates, ability to be grown on non-agricultural land, high lipid, protein, and carbohydrate content, and tolerance of poor water quality are just a few characteristics that make it an attractive feedstock. Unlike conventional feedstocks, algae are less likely to cause deforestation, soil erosion and water pollution (Shi et al., 2018). In response to Canada's ambitious climate goals, one start-up called Algaenious Labs has taken advantage of algae's potential, developing a patented methodology to produce ethanol, lipids and protein in a single, multi-step process.

This report will cover a thorough and inclusive life cycle assessment of Algaenious Labs, studying their environmental impact. It will investigate the carbon footprint of each production process in a gate-to-gate analysis conducted using OpenLCA. By comparing the results to the carbon footprint of other feedstock sources, such as corn, the report will deduce whether algae truly are an environmentally superior feedstock measured in terms of its Global Warming Potential (GWP). Comparing algae to corn as a feedstock for lipids, proteins and ethanol will be the main scope of our investigation, answering the following research question: *"Does algae serve as an environmentally superior alternative to other conventional feedstocks such as corn?"*

This report aims to shed light on the potential of using algae as a substitute for other feedstocks in hopes of accelerating the transition to a cleaner and greener world and meeting global climate goals.

Methodology

Model Structure and bounds:

The LCA model used in this assessment utilised the ecoinvent 3.8 database, kindly provided by Dr. Tu. This database includes some location specific inputs (such as BC's low voltage power supply), however some other flows represent European markets (Moreno Ruiz et al., 2021). Furthermore, most flows used were defined within the model and would not capture the true wide range of impacts. Given the limited resources and access to data, this LCA only assesses the cradle-to-cradle impacts of these products. This scope includes the processes that are directly related to the production of the three products, similar to the concept of scope 1 & 2 emissions. Notably, the impacts relating to the production, harvesting and drying of the algae feedstock is excluded from this assessment, as well as the downstream impacts pertaining to the use of these products. However, the model did capture energy and chemical flows into and out of the system, and therefore the results presented here have utility in understanding the merit of each production technique in comparison to others.

Algaenius's proposed biorefinery integrates three primary processes: Lipid Extraction, Protein Extraction, and Ethanol Production, each comprising of distinct subprocesses. These processes are inherently interlinked, as the extraction of one component, serves as a pre-treatment of the next, minimising energy loss, and biomass wastage. Furthermore, the pilot facility is entirely electrified, looking to leverage the clean energy provided in BC.

1: Lipid Extraction:

The process begins with purchased dried algae, with an assumed composition of 37% lipids, 39% protein, 31% carbohydrates, and 3% inorganic (ash) (Tu et al., 2018). During the

lipid extraction process, hexane is used to disrupt the cell wall, and selectively solubilise lipids. To achieve a favourable extraction rate, a solids loading ratio of 33% was used (1Kg biomass to 2Kg solvent). The hexane-algae mixture then undergoes centrifugation to separate the lipid-containing hexane (supernatant) from cellular material (pellet), following this, solvent recovery occurs to yield lipid. Figure 1 shows the model graph of this process, while Table 1 presents the inventory.

1.1: Hexane Treatment:

Purchased dried algae feedstock is mixed with hexane, breaking down the cell wall and releasing its contents. Hexane, a non-polar solvent, selectively solubilises lipids. In our model, 95% of the solvent used is assumed to be internally recovered, sourced from the lipid extraction phase. The defatted algae, rich in proteins and carbohydrates, is directed to the protein extraction process.

1.2: Lipid Extraction:

To isolate the lipids, the hexane-lipid suspension undergoes solvent recovery, also allowing the process to be as closed-loop as possible. The energy required for solvent recovery is assumed to be the latent heat of vaporization for hexane. Once the solvent is evaporated, lipids precipitate out of the solution, ready to exit the system.

1: Model Graph

Figure 1: Model graph of lipid extraction process

1: Inventory Table

Table 1: Inventory of lipid extraction process

Flow Name	Amount	Unit
Inputs		
Feedstock Dry Algae	3.70	Kg
Hexane (95% recovered, 5% virgin)	7.4	Kg
Electricity (BC Low Voltage)	0.111	kWh
Outputs		
Lipids	1	Kg
Defatted algae	2.7	Kg

2: Protein Extraction:

Protein extraction involves further disrupting the defatted algae and extracting the proteinaceous content using ethanol. Similar assumptions and procedure were followed in this step as in in lipid extraction as seen in Figure 2 and Table 2

2.1: Ethanol Treatment:

The defatted algae is mixed with ethanol, selectively pulling the cellular protein content into solution. This ethanol-biomass mixture is centrifuged, separating carbohydrate-rich cellular debris and the supernatant of protein and ethanol. The cellular debris can then be sent to the next phase (3.1: enzymatic hydrolysis) while the supernatant then undergoes solvent recovery.

2.2: Protein Extraction

The protein-ethanol supernatant, is then passed through a solvent recovery step, with the energy requirement again assumed to be the latent heat of vaporization for ethanol. The precipitated protein can then leave the system.

2: Model Graph

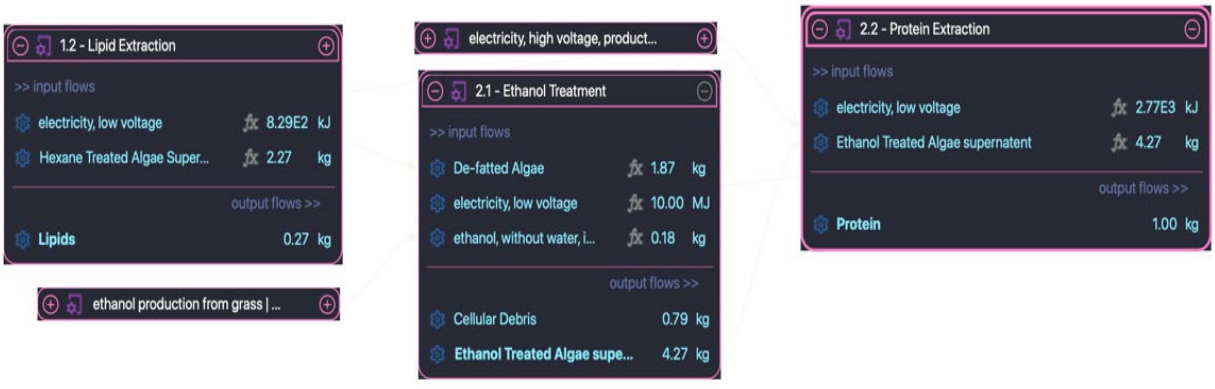


Figure 2: Model graph of protein extraction

2: Inventory Table

Table 2: Inventory of protein extraction process

Flow Name	Amount	Unit
Inputs		
De-Fatted Algae	1.87	Kg
Ethanol	3.74	Kg
Electricity	0.056	kWh
Outputs		
Protein	1	Kg
Cellular Debris	0.79	Kg

3: Ethanol Production:

The ethanol production phase aims to convert the complex carbohydrates, such as cellulose, found in the cellular debris into ethanol. This process consists of three sub-processes, including enzymatic hydrolysis, fermentation, and distillation which are outlined in Figure 3. The inventory of this process can be found in Table 1

3.1: Enzymatic Hydrolysis:

Cellular debris, now primarily composed of carbohydrates, is treated with saccharification enzymes 60°C. These enzymes break down complex sugars into fermentable simple sugars, by hydrolysing the long polymer chains into monomeric sugars. To improve enzyme mobility at a suitable solids loading, water is added to cellular debris. This process is relatively energy intensive given the requirement to heat an entire batch to 60˚C. Once

hydrolysis is complete, the hydrolysed cellular debris can be fermented by yeast in the next stage.

3.2: Fermentation:

During fermentation, yeast is pitched into the hydrolysed cellular debris, consuming the sugars and producing ethanol. As well as ethanol, the yeast also release CO_2, however this CO_2 is biogenic, meaning it will have a net 0 GWP. The yeast was assumed to be capable of achieving a final ethanol concentration of 13%, as yeast cells begin to die off above this concentration. Following fermentation, yeast and the remnants of the biomass flocculate out of suspension, and can be collected from the bottom of the fermentation vessel. This solid material leaves the system boundary as biowaste, which is likely to be used in other industries.The product of fermentation is fermentation broth, which is then sent to distillation to concentrate the ethanol.

3.3: Distillation:

Distillation of the fermentation broth concentrates the relatively low-ethanol-content broth to 95% ethanol, which is a market standard product. This process involves heating the mixture to above the evaporation temperature of ethanol, but below that of water. This draws the ethanol up the column (still) where it condenses back into a liquid to be collected. The amount of energy required to distill ethanol is challenging to determine, however a study conducted on a farm-scale operation concluded that 5.706 MJ of energy was needed (Stampe et al., 1983). At this point the process is complete, with the liquid waste being released into municipal sewer system.

3: Model Graph

Figure 3: Model graph of ethanol production

3: Inventory Table

Table 3: Ethanol production inventory

Flow Name	Amount	Unit
Inputs		
Cellular debris	8.65	Kg
Enzymes	0.1	Kg
Yeast	0.055	Kg
Electricity	3.223	kWh
Water	8	kg
Outputs		
Ethanol	1	Kg
Bio-waste (spent yeast and cellular debris)	10	Kg
Waste water	6.96	Kg

Algaenious Labs' single multi-step process

Algaenious Labs has developed a patented multi-step process to produce lipids, ethanol, and proteins from microalgae. As a preliminary step, this methodology is currently being adopted on a small scale. The process begins with pre-treating the bought, dried microalgae with hexane to selectively dissolve lipids. The hexane pre-treatment disrupts the algae cells, facilitating the extraction of the lipids through the collection of the supernatant after centrifugation. The solvent is evaporated with the application of heat to isolate the lipids, and 95% of the hexane is recovered and recycled into the process. The residue after centrifugation comprises of cellular debris containing proteins. The protein is extracted with the addition of ethanol as ethanol dissolved proteins. After another centrifugation, the supernatant is extracted and collected. With the addition of heat, the solvent is evaporated to recover and recycle the ethanol while isolating proteins. The residue after centrifugation contains cellular debris and undergoes enzymatic hydrolyses with the addition of cellulase enzymes at optimum pH and temperature. The role of enzymatic hydrolysis is to break down complex polysaccharides into simple sugars to facilitate fermentation. The carbohydrates undergo fermentation with the addition of yeast and heat to yield ethanol. Distillation takes place to produce distilled and concentrated ethanol which serves as the third and final produce of Algaenious Labs.

Conducting the LCA for Algaenious Labs

To investigate the life cycle assessment of the gate-to-gate analysis, OpenLCA was used as a tool. OpenLCA is an open-source software program that conducts Sustainability and Life Cycle Assessments. To study the carbon footprint of Algaenious Labs, the software was used to document the various inputs and outputs associated with each flow process of the

Determining the Carbon Footprint of Corn as a Feedstock

An LCA was done on a corn biorefinery for the production of corn-based ethanol. The main product from the corn biorefinery is ethanol with co-products of corn oil and protein dense animal feed (Gerrior et al., 2022). The methodology of this process is first by dry milling the corn feedstock, and then integrating a fiber separation technology to separate fiber from the corn feedstock, along with the corn oil extraction in the same step (Gerrior et al., 2022). The starch from corn is hydrolyzed, so that during the fermentation and distillation process in the next step, a dilute ethanol product is produced (Gerrior et al., 2022). In this entire process, there are other by-products and co-products, but for the relevancy of this report we will only mention the co-products of corn oil and Hi-Pro—comprised of 42% protein (Gerrior et al., 2022). At the end of the biorefinery process, the algae slurry is recycled back to the beginning to be utilized in the dry milling process(Gerrior et al., 2022).

The results of Gerrior et al.'s 2022 LCA study involved a scope of a cradle to gate analysis, which is larger than the scope this report covers, and the method used to evaluate carbon footprint was the midpoint ReCiPe LCIA. From there on, the LCA was conducted in OpenLCA with its main data collected from IGPC (Integrated Grain Processor's Cooperative) Ethanol and supplementary data from GREET version 1.8d (Gerrior et al., 2022). The data collected from this LCA literature was altered and adjusted to match the functional units in our report, as well as only looking at the data that was relevant in a gate-to-gate analysis for better comparison to our LCA study.

Assumptions

A plethora of assumptions were made to conduct the LCA for Algaenious Labs, the most significant one being the accuracy and reliability of data. Since primary data was inaccessible during the data collection, all of the figures were taken from secondary sources which may have resulted in inaccuracies in the total GWP results.

Algae composition:

According to (Tu et al., 2018), the ethanol, lipid and protein composition was assumed to be 27%, 39% and, 31% respectively.

Solvent:

The ratio of ethanol and hexane to the biomass content was assumed to be 200% and the solvent recovery rate was assumed to be 95%. The small-scale nature of the project drove the assumption of a 100% efficiency rate for ethanol and hexane treatment.

Energy:

Centrifugation is a key step in the Algaenious Labs' process. The Alfa Laval Centrifuge from the company "KyteCentrifuges" requires 37 kWh of electricity for centrifugation. To centrifuge 1000 L of solution, 10 KWh of electricity was assumed to be used. Moreover, recovering and recycling the solvents required 365 KJ/Kg of electricity for hexane and 846 KJ/Kg for ethanol.

Producing protein, ethanol, and lipid from corn

The LCA conducting for Algaenious Labs was compared to the carbon footprint of other conventional pathways using corn as an alternate source of feedstock.

LCA Results & Discussion

After creating the model, we were able to calculate the individual GWP totals for each final product. When producing 1 kg of ethanol, 3.938 kg CO2e is emitted. When producing 1 kg of lipids, 3.820 kg CO2e is emitted. Lastly, when producing 1 kg of proteins, 0.920 kg of CO2e is emitted. These values can be seen as visualized in Figure 4. Given the inherent interconnection between all three processes, allocating a GWP impact to a single product fails to accurately portray the benefits of creating multiple products from the same feedstock. One area of future research could be the inclusion of the avoided impacts of external production of these products.

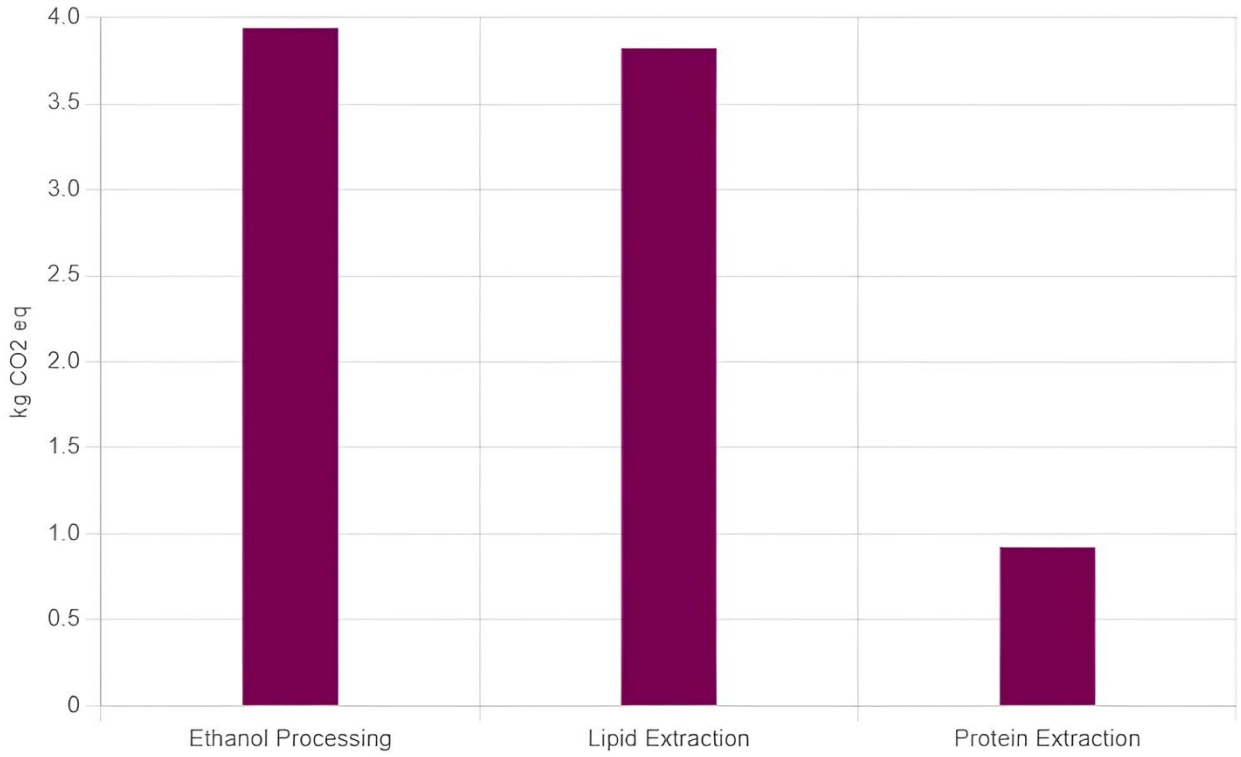


Figure 4:Visualization of GWP totals of each process

Global Warming Potential

For the three processes modeled, there were common CO2e sources that contributed to all pathways. The percentage breakdowns can be seen visualized as a pie chart in Figure 5. All three processes required a hexane treatment which accounted for the greatest percentage of total emissions in each process. This was due to the high electricity consumption that was needed for the treatment process. Because this is the single process to extract lipids from microalgae, the hexane treatment accounted for 97% of the total emissions in the lipid pathway. The next process used was an ethanol treatment which was used in the production of proteins and ethanol itself. This process accounted for 14% of total emissions in the protein pathways and 10% of total emissions in the ethanol pathway. Similar to the hexane, nearly all emissions coming from the ethanol treatment are due to electricity consumption.

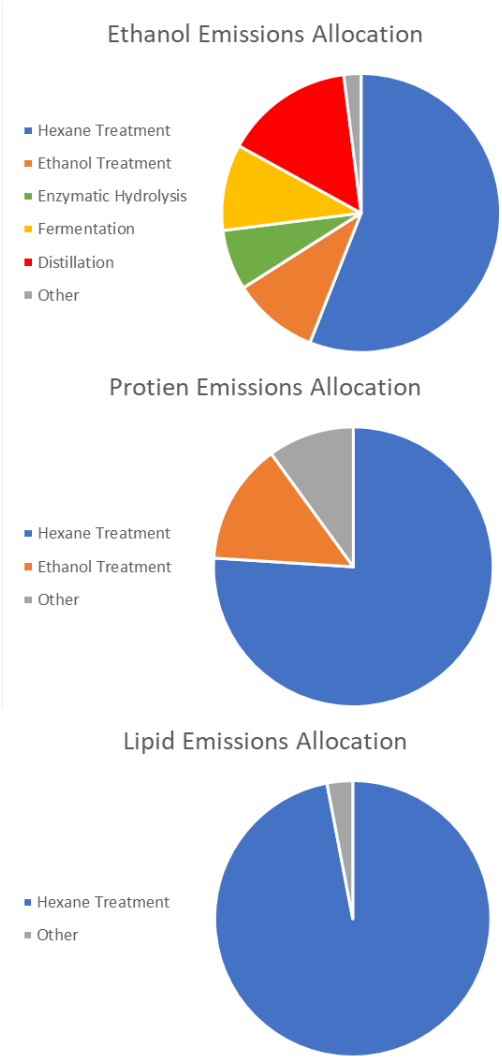


Figure 5: A visual breakdown of emission contributions in each pathway

The final pathway with the most additional steps is ethanol production which requires enzymatic hydrolysis, fermentation, and distillation steps. Enzymatic hydrolysis is first and accounts for 7% of the total emissions when producing ethanol. Most of this comes from more electricity use but a small portion comes from the production of enzymes themselves. The next

step is fermentation which accounts for 10% of the total emissions. The entirety of these emissions comes from the treatment of biowaste via industrial composting. The last step required is the distillation process which accounts for 15% of the total emissions. Similar to the other processes, nearly the entirety of distillation emissions comes from electricity use.

Comparison and Importance

After carefully modelling out the whole process from a gate-to-gate perspective and calculating the GWP of each co-product, the final question to answer was if this technology provided an environmentally superior pathway to existing feedstocks. To answer this question, we reviewed other existing feedstocks that had the potential of producing ethanol, lipids, and proteins. One feedstock that immediately fit our criteria well was corn. Corn is already a popular feedstock used to produce ethanol. The primary co-product of that process is animal feed, which is composed of proteins, lipids, and other biomass such as fiber. We wanted to find an LCA done on a corn biorefinery producing ethanol, and further processing animal feed into corn oil and proteins so we could compare the GWP of the two feedstocks and pathways.

For this, we chose a study conducted by Gerrior et al., who's 2022 LCA on a corn biorefinery that produced ethanol, corn oil, high-protein animal feed, and traditional animal feed. The LCA used a cradle-to-gate scope which was broader than our own scope, so specific values had to be taken and added together to achieve a comparable gate-to-gate GWP value. Additionally, they used a different functional until than us, so conversions were done to each have a functional unit of CO2e per kg of EtOH.

After all that, it was found that producing 1 kg of ethanol with co-products from corn in a similar scope, it emitted 4.386 kg of CO2e. The bulk of these emissions come from burning natural gas for heating during the processes, but other contributors come from electricity use, enzyme use,

and urea use. When comparing this value with our results of 3.938 kg of CO2e from 1 kg of ethanol, we can see that there is a 0.448 kg of CO2e reduction per kg of ethanol solely in the processing steps when using algae as a feedstock instead of corn. Although this seems like an insignificant amount, the economies of scale can easily take into effect and a 10% reduction in emissions during processing will create significant reductions down the road.

This comparison demonstrates the importance of this project with finding alternate pathways of processing that can have a lower carbon impact all while backing up claims with data. As algae is a third-generation feedstock, they are known to have higher environmental performances compared to other feedstocks used for biofuel production *(Dutta et al., 2022). One of the important advantages of using algae as a feedstock is the ease of cultivation—as it doesn't require agricultural land and has lower energy consumption in comparison to other feedstocks *(Dutta et al., 2022). Microalgae cells are more efficient in terms of productivity as their growth rates are exceptionally high, their capability of fixing CO2 from the environment to regulate their metabolism all while contributing to greenhouse gas mitigation *(Goswami et al., 2022). These are all important factors to consider as we transition into a lower carbon economy. Finding as many options as possible for reductions will be pivotal in avoiding future climate disaster, and sourcing ethanol, lipids, and proteins from microalgae may be an important tool for doing so.

Sensitivity Analysis

A sensitivity analysis was conducted in our LCA model to see how the variation in key input parameters affected the environmental performance indicators, which in our case was how it affected the GWP in our LCA model. The key parameter we identified was the energy consumption, in megajoules per kilogram CO2e, that was required for distillation. In our sensitivity analysis, we compared different amounts of electricity consumption from 2.85MJ to

11.4MJ and the results gave us a difference of –0.149kg CO2e. The minor change shown reflects the negligible impact of electricity consumption on GWP in our model, which is visualized in Figure 6. The results of the sensitivity analysis provide insight into the parameters that could have significant contributions in the GWP variability, which is important and can be used to better improve the potential environmental impacts of algae processing.

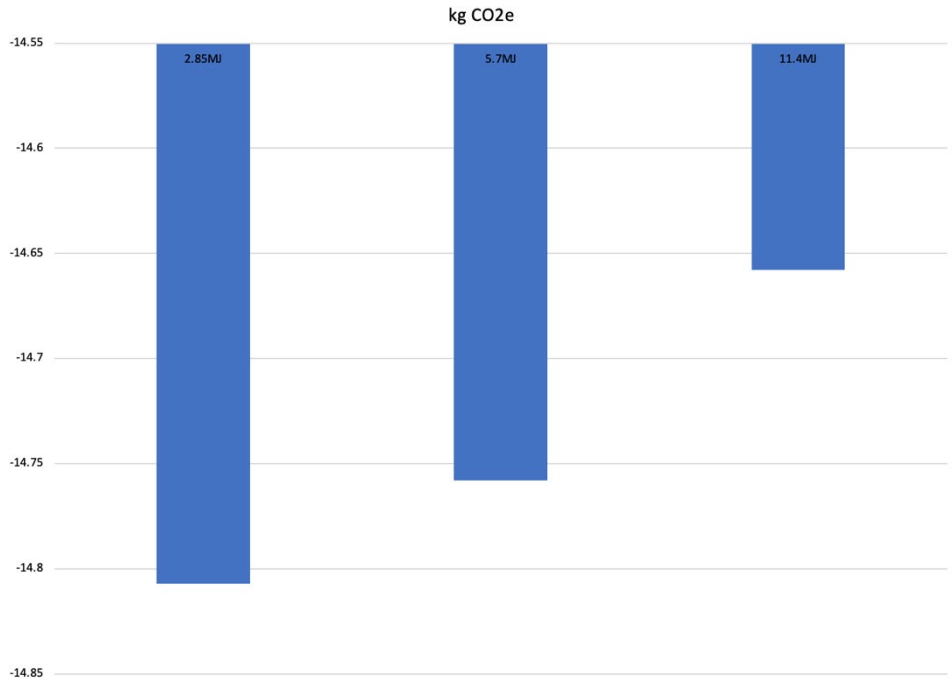


Figure 6: Graph of CO2 emissions in kilograms per megajoules in energy consumption for distillation

Limitations

The LCA model is created with the assumptions of current technology practices and can therefore only provide an assessment for current practices. The limitation with that is not being able to predict future developments, as technological advancements may alter the processes and result in significant changes to the environmental performance of the production pathways.

Data quality and the availability of data are also important factors in an LCA, as the data should be sourced from reliable and updated sources. There are other programs such as Simapro and GaBi which are LCA software programs used in commercial industries and typically require paid licenses to use. Whereas the program we used—OpenLCA is free and comes with basic sets of built-in databases. However, the limitation of that is not having sufficient data that covers data specific to our product or processes. As well as existing inputs in OpenLCA may not be updated frequently, which can then affect the accuracy of our results.

Lastly, the literature that was used for this project came from a variety of different sources. Given the complex nature of this project, the range of sources we used was imperative to support the claims and data presented in this report. Although this approach provided validity and clarity of our research, it also comes with a possible limitation—specifically the possibility of discrepancies between the derived information from different sources of literature and the actual processes in our project. With that being said, it is important to take into consideration the challenges of gathering literature relevant to our project and apply it to our research.

Conclusion

Algae has made its breakthrough appearance in the biorefinery world, known for its high environmental performance and attractive characteristics. Its ability to reproduce at rapid rates, ease of cultivation especially on non-agricultural land, tolerable of poor water quality, and its carbohydrate, protein, and lipid content make this feedstock hard to ignore. With the urgency needed in climate action, researchers and scientists are desperately looking for alternatives and innovative pathways to drastically minimize carbon footprints while also improving efficiency

and outputs. This report focused on the LCA of Algaenious Labs and its project of using algae as a feedstock for lipids, proteins, and ethanol to address the research question of, “Does algae serve as an environmentally superior alternative to other conventional feedstocks such as corn?”

Within the methodology, this report outlined the steps to conduct the multi-step process to produce lipids, proteins, and ethanol, including the goal and scope of the LCA. This was then compared with the methodology of a corn biorefinery and its LCA study which we defined in this comprehensive report. The Algaenious Labs' life cycle assessment involved essential assumptions from literature due to a lack of primary data. Assumptions regarding algae composition, solvents, and energy were also made which suggested the need for further research and literature on the topic.

The total GWP from processes to produce 1 kg of ethanol, lipids, and proteins was 3.938 kg CO2e, 3.820 kg CO2e, and 0.920 kg CO2e respectively. Comparative analysis with corn-based pathways revealed a 0.448 kg CO2e reduction per kg of ethanol in Algaenious Labs' processes. However, limitations, including assumptions about current technology and data quality challenges, call for further refinement of the model.

Future work around this project could be conducted on a real-life biorefinery with these same processes, as well as integrating a cradle-to-grave scope of the LCA. Additionally, more research could be done on each process to find methods of reducing GHG emissions even further. This project highlights the potential of future microalgae biorefineries providing valuable products that can help bring us to a lower carbon economy and avoid a large-scale climate disaster.

Contribution Statement

The graphic abstract, abstract, introduction, and Algaenious Labs' multi-step methodology, and assumptions were written by Vinya. The corn biorefinery LCA methodology, comparison and importance, sensitivity analysis, and limitations in the results & discussion, half of the conclusion and contribution statement was written by Annie. The LCA results and discussion, global warming potential, comparison and importance in the results & discussion, and half of the conclusion was written by James. Sam produced the entire LCA model and wrote the methodology of conducting the LCA for Algaenious Labs'.

Equitable responsibility refers to the fair and equal distribution of work between members of a group. In order to create a strong work environment, equal collaboration was vital to the success of the project. Fair collaboration required good communication from each member, especially with conflicting schedules. Therefore, the utilization of Discord was especially helpful in the coordination of meetings.

References

Alfa Laval. (n.d.). *PX 55 & PX 55EX Medium-capacity disc stack centrifuge for fats and oils refining*. Retrieved November 30, 2023, from https://www.alfalaval.com/globalassets/documents/products/separation/centrifugal-separators/disc-stack-separators/px-55-disc-stack-centrifuge.pdf

Dutta, L., Baruah, J., & Kalita, E. (2022). Biorefinery Approach for Sustainable Biodiesel and bioethanol production from microalgae. *Clean Energy Production Technologies*, 31–53. qhttps://doi.org/10.1007/978-981-19-0793-7_2

Gerrior, D., Delsoz Bahri, K., Kermanshahi-pour, A., Eckelman, M. J., & Brar, S. K. (2022). Life cycle assessment and techno-economic analysis of a novel closed loop corn ethanol biorefinery. *Sustainable Production and Consumption*, *30*, 359–376. https://doi.org/10.1016/J.SPC.2021.12.007

Moreno Ruiz, E., FitzGerald, D., Symeonidis, A., Ioannidou, D., Müller, J., Valsasina, L., Vadenbo, C., Minas, N., Sonderegger, T., & Dellenbach, D. (2021). *Documentation of changes implemented in ecoinvent database v3.8*.

Stampe, S., Alcock, R., Westby, C., & Chisholm, T. (1983). Energy consumption of a farm-scale ethanol distillation system. *Energy in Agriculture*, *2*(C), 355–368. https://doi.org/10.1016/0167-5826(83)90030-X

Goswami, R. K., Agrawal, K., & Verma, P. (2022). Microalgae biomass biorefinery: A sustainable renewable energy feedstock of the future. *Clean Energy Production Technologies*, 1–29. https://doi.org/10.1007/978-981-19-0793-7_1

Tu, Q., Eckelman, M., & Zimmerman, J. B. (2018). Harmonized algal biofuel life cycle assessment studies enable direct process train comparison. Applied Energy, 224, 494–509. https://doi.org/10.1016/J.APENERGY.2018.04.066