A Multi-Objective Optimization Model for an Algal Biofuel Supply Chain Integrating Resource Recirculation

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Abstract

Demand for energy is only expected to grow in the near future due to global population growth which result to a rise in environmental concerns with the diminishing supply of fossil fuels along with the rise of greenhouse gas emissions. Biofuel production from microalgae biomass has been proven to be a viable alternative for fossil fuels; however, challenges are faced regarding its economic sustainability. The integration of processes to yield various high-value bioproducts have been implemented to raise profitability and sustainability. Incorporating a circular economy outlook, recirculation of resource flows is maximized to satisfy economic and environmental sustainability through waste minimization. Previous modelling studies have not looked into the opportunity of integrating continuous recirculation and reuse of resources. In this work, a novel multi-objective optimization model is developed centered on an algal biofuel supply chain that simultaneously optimizes cost and environmental impact, integrates inputs and processes aimed towards a closed loop process flow, and adopts the principle of resource recovery and recirculation. A case study is solved as proof of concept and to illustrate the design methodology, optimal solutions based on economic and environmental performance are analyzed. Scenario analysis is also performed to analyze system behavior under varying conditions.

Keywords
Algal biofuels, Supply chain, Multi-objective optimization.

1. Introduction
Global energy demand is forecasted to unwaveringly increase along with rapid economic and population growth. According to the International Energy Agency (2019), with our present energy strategies, global energy demand would rise by 1.3% annually until 2040. With that in mind, our society has been heavily dependent on fossil fuels as our primary energy source for the longest time. The depleting supply of fossil fuels along with its associated greenhouse gas emissions has become a global environmental concern. This is evidence that further research into sustainable energy source alternatives such as nuclear, solar, wind, hydropower, and biofuels is essential to solving this crisis. Biodiesel has been considered the main substitute for fossil fuel (Ahmad et al., 2011). Microalgae is acknowledged as one of the most valuable feedstocks for biofuel production with its high productivity and carbon sequestration potential (Singh and Gu, 2010). However, the high production costs of microalgal biofuels rivals with the comparatively inexpensive costs of fossil fuel production. Microalgal biodiesel production requires a great amount of energy which equates to higher production costs. In addition, the processes involved generate lots of waste including leftover biomass waste. To be able to maximize biomass utilization, integrated methods are performed for the entire value chain through the introduction of other bioproducts into the algal biofuel production system (Budzianowski, 2017).

Various researchers have already looked into the integration of different processes in a microalgal biorefinery supply chain. De Bhowmick et al. (2019) envisioned biofuel and biochar co-production alongside high-value bioproducts while generating negligible greenhouse gas emissions. For their visualized conceptual model on process integration, zero waste outflow was the priority. Comparably, studies by Mitra and Mishra (2019), as well as Mohan et al. (2020), proposed self-sustaining algal biorefinery design models with a closed-loop approach regarding the byproduct utilization in the system. Mohan et al. (2020) integrated monomeric sugars, bioalcohols, and biohydrogen into the process flow to utilize leftover algal biomass from the extraction process. Furthermore, Mitra and Mishra (2019) included sludge and flue gas into their process inflows and outflows along with biofertilizers, jet fuels, nutraceuticals, and c-phycocyanin as biorefinery byproducts in its process integration.

Despite proposing conceptual models for an algal biorefinery, verification of the zero-waste feature of the processes was not presented through any mathematical assessment in the previously mentioned studies. Wu and Chang (2019) evaluated an integrated microalgal biorefinery from a process system engineering standpoint using life cycle assessment and techno-economic assessment methodologies to appraise the biorefinery's environmental and economic benefits. Their biorefinery production system involved processes that generate bioenergies and bioalcohols that eventually cycle back to act as feedstock in the cultivation process. Yet, their research only provided a methodology for a multi-objective optimization algorithm but failed to present the results of the algorithm. Numerous optimization models developed for algal biofuel supply chain design have emerged in the recent years. Babazadeh (2017) formulated a superstructure optimization model applied to an algal biodiesel supply chain. The multi-period mixed integer model focused on total cost NPV minimization. Comparatively, Ezzati et al. (2018) developed a mixed integer linear programming model for the design of a microalgal and jatropha biodiesel supply chain network aiming to minimize its overall costs. The end products involved in this supply chain are biodiesel and glycerin. Moreover, Ghelichi et al. (2018) included fertilizer in its algal biodiesel supply chain network along with biodiesel and glycerin. This study looked into overall cost minimization incorporating a min-max regret methodology to determine the optimal scenario. However, it is observed that the optimization models developed in the cited studies only focused on a single objective involving economic impact which points to the possibility that their solution may not be environmentally sustainable.With that, a multi-objective goal programming optimization model was developed by Arabi et al. (2019) for an algal biofuel supply chain network focusing on profit and carbon adsorption maximization. However, the study did not include the recovery and recirculation of input materials into the supply chain.

1.1 Problem Definition
With increased environmental consciousness driven by advances in sustainable development, the implementation of an algal biofuel supply chain network design centered on a zero-waste strategy must be done incorporating resource recirculation to meet demand to incur the least overall costs and environmental impacts for the system. Existing optimization studies that have looked into an integrated algal biofuel supply chains lack environmental sustainability incorporation (Babazadeh, 2017; Ezzati et al., 2018; Ghelichi et al., 2018). However, Arabi et al. (2019) developed an optimization model addressing these environmental shortcomings for algal biofuel supply chains. Looking into environmental impact is critical for an algal biofuel supply chain optimization to arrive with results that meet sustainable development goals. Yet, the recovery and recirculation of resources within the supply chain was not incorporated in the previously mentioned studies. Based on the review performed on present algal biofuel supply chain optimization models, there is a need to develop a mathematical optimization model on an integrated algal biofuel supply chain network that optimizes profit and environmental impact, and incorporates resource recirculation and processes centered on a closed-loop supply chain.

2. Literature Review

2.1 Integrated Algal Biofuel Supply Chain
To combat the large production costs of a stand-alone algal biorefinery, an alternative is mentioned through a multi-product biorefinery that efficiently utilizes all microalgae fractions aiming to improve the economic and environmental performance (Posada et al., 2016). An integrated biorefinery has the advantage of producing nonfuel-based products like biofertilizers, biopharmaceuticals, and biocosmetics, synthesized by algae for the application to different industries (Chandra et al., 2019). The production of an extensive selection of bioproducts from algal biomass promotes technical advancement in the field of sustainability and high value product generation. Andersson et al. (2014) concluded that an industrial symbiosis setup can lead off to environmental benefits for algal biorefinery systems, as they showed that the utilization of CO2 from flue gases and using wastewater as a cultivation medium leads to reduction of global warming potential. In a study by Hemalatha et al. (2019), the cultivation of microalgae cultivated with the use of dairy wastewater displayed a higher fraction of carbohydrates and lipids as to proteins. This depicts the potential of microalgae biomass as feedstock for producing bio-based products with the integration of numerous processes aiming for a closed loop process flow as well as the advantage of using wastewater as a cultivation medium (Khan et al., 2019).

Studies show that industrial wastewater, specifically from agro-based industries, are considered to have high nutrient content which is vastly beneficial for algae cultivation (De Corato et al., 2018; Markou and Georgakakis, 2011). It was found in a review by Gupta et al. (2019) that the use of dairy and food industrial wastewater for microalgae cultivation has promising potential for biomass-to-energy production as no negative features were found regarding its utilization. However, with the numerous amount of chemical oxygen demand (COD) in wastewater, it is important to present methods to either reduce the contaminant concentration, through wastewater pre-treatment, or to control conditions of cultivation to impede contaminants increase using duckweed and microalgae, thus reducing the contamination of biomass (Markou et al., 2018).

2.2 Algal Biofuel Supply Chain Optimization

To achieve the goal of reducing cost and environmental impact for an algal biofuel supply chain, linear programming optimization with economic and environmental objectives is developed. The following works looked into the application of linear programming optimization in an algal fuel supply chain. Babazadeh (2017) formulated a superstructure optimization model applied to an algal biodiesel supply chain. Their system involves feedstock suppliers, collection and preprocessing facilities, biorefineries, distribution centers and customer sinks. The multi-period mixed integer model focused on total cost NPV minimization. Relatively, Ezzati et al. (2018) developed a mixed integer linear programming model for the design of a microalgal and jatropha biodiesel supply chain network aiming to minimize its overall costs. Microalgae and jatropha cultivation, oil gathering, extraction and oil treatment, biorefineries, biodiesel storage facilities and end product consumers were included in this network. The end products involved in this supply chain are biodiesel and glycerin. Ghelichi et al. (2018) looked into overall cost minimization incorporating a min-max regret methodology to determine the optimal scenario. This study included fertilizer in its algal biodiesel supply chain network along with biodiesel and glycerin. The network included cultivation facilities, imported input sources, pretreatment and extraction facilities, biorefineries, storage and distribution centers, and consumer sinks. There were also numerous studies that looked into having multiple objectives, economic and environmental, when assessing the production of biofuels from microalgae. A multi-objective goal programming optimization model was developed by Arabi et al. (2019) for an algal biofuel supply chain network focusing on profit and carbon adsorption maximization. Harvesting, pretreatment, treatment and conversion techniques are included in the model along with customer sinks. Ubando et al. (2017) developed a fuzzy mixed integer nonlinear programming optimization model aiming to support the design of an eco-industrial park centered on algae focusing on the objective of minimizing environmental footprint as well as maximizing profit. A multi-objective target oriented robust optimization model was developed by Sy et al. (2018) for an integrated algal biorefinery focusing on profit maximization and footprint minimization.

3. System Definition

3.1 Supply Chain Network

The integrated algal biofuel supply chain network involves the production facilities necessary for biofuel production, suppliers for the raw materials needed by said facilities, biochar production and anaerobic digestion locations for efficient use of biomass, and the customers to be serviced by the supply chain as presented in Figure 1.

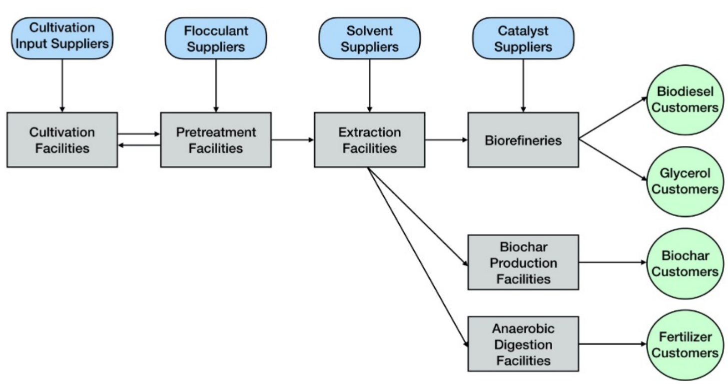

Figure 1. Supply Chain Network

The algal biofuel supply chain to be considered in this study is divided into two main stages. The first stage is focused on the cultivation of microalgal biomass and its conversion into algal oil for biofuel production. The process units included in this section are microalgae cultivation, harvesting and dewatering, and lipid extraction. The second stage involves the downstream processes of the supply chain focusing on the conversion of the algal biomass into the end products such as biodiesel, glycerol, biochar, and fertilizer. The extraction process mainly produces algal lipid which is turned into biodiesel and glycerol through transesterification. Moreover, waste is generated from the lipid extraction process in the forms of solid and liquid algal biomass residues. These residues are converted into bioproducts such as biochar and fertilizer through pyrolysis and anaerobic digestion respectively.

3.2 Resource Recirculation

For the integrated algal biofuel supply chain network, suppliers for material inputs such as water, flocculant, solvent, and catalyst are given alternatives to generate optimization decisions from. These chosen material input suppliers are those that are to be involved in the resource recirculation consideration. This is because these resources are simply materials that aid in the development of the algal biomass in its conversion to biofuel. Each of these materials need to be transported to each facility it will be used in. Resource recovery process units are established inside these facilities to be able to recover said materials if the model chooses to do so. From there, decisions regarding the yield of the waste input determines whether the material is reused in the production system, sold for a given price per kg, or led to waste.

3.3 Multi-periodicity

The optimization model involves multiple time periods to be able to incorporate the longevity of supply chain operations. Capital and operating costs are properly accounted for the algal biofuel supply chain with multiple period consideration.

3.4 Cost Components

For the optimization model, the following cost components will be considered namely: investment costs, operating costs, material purchase costs, transportation costs, and inventory costs. Investment costs refer to the initial capital expenses incurred to construct the algal biofuel supply chain production facilities expressed at a cost per facility basis. Operating costs include labor, overhead, and material costs associated with facility expressed as a cost per time period. Material purchase costs are set for each material input that is used up in the production system expressed as a cost per kg unit. Transportation costs are set from each location option for all suppliers, facilities, and customers involved in the biofuel supply chain expressed as a cost per km travelled. Given that the optimization model considers multiple time periods, inventory costs are included for each material expressed as a periodic cost per kg material.

3.5 Environmental Impact Components

The environmental impact values used for the minimization objective are greenhouse gas (GHG) emissions from production facilities and transportation vehicles. Emissions for facilities are estimated at a rate of GHG emissions per output yield. As for the transport vehicles, the environmental impact is expressed as GHG emissions per distance travelled.

4. Model Formulation

For the supply chain network, a Mixed Integer Linear Programming (MILP) model was developed aiming to make strategic and tactical supply chain decisions, simultaneously optimizing the costs and environmental impacts while satisfying demand and capacity constraints. Supplementary Table 1 presents the indices, relevant parameters, and variables in the model.

4.1 Model Assumptions

All parameters are deterministic and known with certainty. Outputs produced by facilities can be transported on the same period. All transport operations are instantaneous and done with the use of trucks. Processing of algal biomass in all facilities is instantaneous. Capacities for all facilities are fixed throughout the entire study period.

4.2 Objective Functions

The two objectives involved in the mathematical model are maximizing profit and minimizing environmental impact. The profit is calculated by getting the difference between the revenue generated from all products and the overall costs throughout the entire supply chain, presented in Equation (1). Equation (2) defines the revenue for each period which is computed by multiplying the selling price of each product by the total transported output to customers.

$$Profit = \sum_t Revenue_t - Total\ Cost \quad (1)$$
$$Revenue_t = \sum_l \sum_e SPB_t OFB_{let} + \sum_l \sum_f SPG_t OFG_{lft} + \sum_m \sum_g SPC_t OBC_{mgt} + \sum_n \sum_h SPF_t OAF_{nht} \quad (2)$$

The breakdown of the total costs is presented in Equation (3) which are investment costs, operating costs, material purchase costs, transportation costs, and inventory costs. The total investment is the sum product of the fixed costs per facility location and the binary variable for selecting the location, presented in Equation (4).

$$Total\ Cost = Investment + \sum_t Operating_t + \sum_t Purchase_t + \sum_t Transport_t + \sum_t Inventory_t \quad (3)$$
$$Investment = \sum_i FC_i BC_i + \sum_j FP_j BP_j + \sum_k FE_k BE_k + \sum_l FF_l BF_l + \sum_m FB_m BB_m + \sum_n FA_n BA_n \quad (4)$$

The operating costs for each period in the supply chain network are defined as the sum product of the operating costs per facility and the corresponding product output as shown in Equation (5). Equation (6) defines the periodic material purchase costs which is calculated by multiplying the purchase cost per input material with the total amount purchased each period.

$$Operating_t = \sum_i OC_{it} PC_{it} + \sum_j OP_{jt} PP_{jt} + \sum_k OE_{kt} PE_{kt} + \sum_l OF_{lt} PF_{lt} + \sum_m OB_{mt} PB_{mt} + \sum_n OA_{nt} PA_{nt} \quad (5)$$
$$Purchase_t = \sum_i \sum_a PCC_{at} MC_{ait} + \sum_j \sum_b PCP_{bt} MP_{bjt} + \sum_k \sum_c PCE_{ct} ME_{ckt} + \sum_l \sum_d PCF_{dt} MF_{dlt} \quad (6)$$

Equations (7) and (8) indicate the calculations for transportation and inventory costs respectively. The transport costs for each period is the sum product of the transportation costs from one location to another and the total amount of goods transported. Meanwhile, the inventory costs are the unit storage costs for each input and output material and the total inventory level in each facility.

$$Transport_t = \sum_a \sum_i TCC_{ait} OCC_{ait} + \sum_b \sum_j TPP_{bjt} OPP_{bjt} + \sum_c \sum_k TEE_{ckt} OEE_{ckt} + \sum_d \sum_l TFF_{dlt} OFF_{dlt} + \sum_i \sum_j TCP_{ijt} OCP_{ijt} + \sum_j \sum_i TPC_{jit} OPC_{jit} + \sum_j \sum_k TPE_{jkt} OPE_{jkt} + \sum_k \sum_l TEF_{klt} OEF_{klt} + \sum_k \sum_m TEB_{kmt} OEB_{kmt} + \sum_k \sum_n TEA_{knt} OEA_{knt} + \sum_l \sum_e TFB_{let} OFB_{let} + \sum_l \sum_f TFG_{lft} OFG_{lft} + \sum_m \sum_g TBC_{mgt} OBC_{mgt} + \sum_n \sum_h TAF_{nht} OAF_{nht} \quad (7)$$
$$Inventory_t = \sum_i ICO_{it} LCO_{it} + \sum_j IPO_{jt} LPO_{jt} + \sum_k IEO_{kt} LEO_{kt} + \sum_l IFO_{lt} LFO_{lt} + \sum_m IBO_{mt} LBO_{mt} + \sum_n IAO_{nt} LAO_{nt} + \sum_i ICI_{it} LCI_{it} + \sum_j IPI_{jt} LPI_{jt} + \sum_k IEI_{kt} LEI_{kt} + \sum_l IFI_{lt} LFI_{lt} + \sum_m IBI_{mt} LBI_{mt} + \sum_n IAI_{nt} LAI_{nt} \quad (8)$$

The environmental impact minimization objective is defined in Equation (9). It is the sum of the impact from process facilities and transport operations. Impacts for facilities are defined in Equation (10) as a sum product of the environmental impact per output of each facility and their corresponding total produced output. As for the transport impact, the environmental impact is expressed as the product of the impact per transported material and the total amount of transported material in the network as shown in Equation (11).

$$Total\ Impact = \sum_t Process\ Impact_t - \sum_t Transport\ Impact_t \quad (9)$$
$$Process\ Impact_t = \sum_i EIC * PC_{it} + \sum_j EIP * PP_{jt} + \sum_k EIE * PE_{kt} + \sum_l EIF * PF_{lt} + \sum_m EIB * PB_{mt} + \sum_n EIA * PA_{nt} \quad (10)$$
$$Transport\ Impact_t = \left[\sum_a \sum_i OCC_{ait} + \sum_b \sum_j OPP_{bjt} + \sum_c \sum_k OEE_{ckt} + \sum_d \sum_l OFF_{dlt} + \sum_i \sum_j OCP_{ijt} + \sum_j \sum_i OPC_{jit} + \sum_j \sum_k OPE_{jkt} + \sum_k \sum_l OEF_{klt} + \sum_k \sum_m OEB_{kmt} + \sum_k \sum_n OEA_{knt} + \sum_l \sum_e OFB_{let} + \sum_l \sum_f OFG_{lft} + \sum_m \sum_g OBC_{mgt} + \sum_n \sum_h OAF_{nht}\right] * EIT \quad (11)$$

Since the model has dual objectives, there must be a balance between the economic and environmental objectives to generate the optimal solution. The objective function is defined as the maximization of the least desired value to balance the two objectives as seen in Equation (12) (Solis et al., 2020). Equations (13) and (14) defined the efficiencies for each objective, obtained by getting the ratio of the attained improvement, which is actual value subtracted from the worst possible one, and the potential improvement, which is the best possible value subtracted from the worst possible one. The best possible values for the two objectives are acquired through the optimization of each corresponding objective using a single objective linear programming model. The assumption is that the worst possible value for the environmental impact objective is its value when the profit objective is optimized, and vice versa.

$$Max\ Z = min\left[Eff_{Profit}, Eff_{Impact}\right] \quad (12)$$
$$Eff_{Profit} = \frac{Profit_{worst} - Profit}{Profit_{worst} - Profit_{best}} \quad (13)$$
$$Eff_{Impact} = \frac{Impact_{worst} - Impact}{Impact_{worst} - Impact_{best}} \quad (14)$$

With the nonlinear nature of the objective function defined above, it is necessary to include linearizing constraints to the model to make sure that the optimization model generates the optimal solution. Equations (16) and (17) illustrate that the final value for efficiency is equal to the minimum of the efficiencies of the two objectives (Solis et al., 2020).

$$Max\ Z = Efficiency \quad (15)$$
$$Efficiency \leq Eff_{Profit} \quad (16)$$
$$Efficiency \leq Eff_{Impact} \quad (17)$$

4.3 Constraints

The model constraints regarding the demand for the various products of the supply chain network are presented in Equations (18) to (21). The total amount of each product transported to each customer location must be greater than or equal to the customer demand for each product namely, biodiesel, glycerol, biochar, and fertilizer in every location.

$$\sum_l OFB_{let} \geq DB_{et} \qquad \forall e\ \forall t \quad (18)$$
$$\sum_l OFG_{lft} \geq DG_{ft} \qquad \forall f\ \forall t \quad (19)$$
$$\sum_m OBC_{mgt} \geq DC_{gt} \qquad \forall g\ \forall t \quad (20)$$
$$\sum_n OAF_{nht} \geq DF_{ht} \qquad \forall h\ \forall t \quad (21)$$

The capacity constraints define the processing capability of each facility as defined in Equations (22) to (27). The overall production output of each facility is set to be less than or equal to the process capacity of that facility multiplied by the binary variable for the construction of each facility.

$$PC_{it} \leq BC_i CC_i \qquad \forall i\ \forall t \quad (22)$$
$$PP_{jt} \leq BP_j CP_j \qquad \forall j\ \forall t \quad (23)$$
$$PE_{kt} \leq BE_k CE_k \qquad \forall k\ \forall t \quad (24)$$
$$PF_{lt} \leq BF_l CF_l \qquad \forall l\ \forall t \quad (25)$$
$$PB_{mt} \leq BB_m CB_m \qquad \forall m\ \forall t \quad (26)$$
$$PA_{nt} \leq BA_n CA_n \qquad \forall n\ \forall t \quad (27)$$

The product input to output conversion is defined in process constraints shown in Equations (28) to (33). For the conversion of product inputs to their corresponding outputs, the sum of the ending inventory of the previous period and the total delivered amount of inputs is set to be greater than or equal to the overall production output of the facility multiplied by the conversion output yield.

$$PC_{it} * YC \leq LCI_{it-1} + \left[\sum_a OCC_{ait} + \sum_j OPC_{jit}\right] \forall i\ \forall t \quad (28)$$
$$PP_{jt} * YP \leq LPI_{jt-1} + \left[\sum_b OPP_{bjt} + \sum_j OCP_{ijt}\right] \forall j\ \forall t \quad (29)$$
$$PE_{kt} * YE \leq LEI_{it-1} + \left[\sum_c OEE_{ckt} + \sum_j OPE_{jkt}\right]\ \forall k\ \forall t \quad (30)$$
$$PF_{lt} * YF \leq LFI_{lt-1} + \left[\sum_d OFF_{dlt} + \sum_k OEF_{klt}\right] \forall l\ \forall t \quad (31)$$
$$PB_{mt} * YB \leq LBI_{mt-1} + \sum_k OEB_{kmt} \qquad \forall m\ \forall t \quad (32)$$
$$PA_{nt} * YA \leq LAI_{nt-1} + \sum_k OEA_{knt} \qquad \forall n\ \forall t \quad (33)$$

The constraints regarding the binary variables for the facility operations are defined in Equations (34) to (39). The sum of the binary variables for each facility type is set to be less than or equal to the total number of facilities considered in the model.

$$\sum_i BC_i \leq I \quad (34)$$
$$\sum_j BP_j \leq J \quad (35)$$
$$\sum_k BE_k \leq K \quad (36)$$
$$\sum_l BF_l \leq L \quad (37)$$
$$\sum_m BB_m \leq M \quad (38)$$
$$\sum_n BA_n \leq N \quad (39)$$

Equations (40) and (45) present the relationship between the transported amount from each facility in a period to the production output in that period. The overall transport amount is set to be less than or equal to the ending inventory of the previous period plus the production amount of the current period.

$$\sum_j OCP_{ijt} \leq LCO_{it-1} + PC_{it} \quad \forall i\ \forall t \quad (40)$$
$$\sum_k OPE_{jkt} \leq LPO_{jt-1} + PP_{jt} \quad \forall j\ \forall t \quad (41)$$
$$\sum_l OEF_{klt} + \sum_m OEB_{kmt} + \sum_n OEA_{knt} \leq LEO_{it-1} + PE_{it} \quad \forall k\ \forall t \quad (42)$$
$$\sum_e OFB_{let} + \sum_f OFG_{lft} \leq LFO_{lt-1} + PF_{lt} \quad \forall l\ \forall t \quad (43)$$
$$\sum_g OBC_{mgt} \leq LBO_{mt-1} + PB_{mt} \quad \forall m\ \forall t \quad (44)$$
$$\sum_h OAF_{nht} \leq LAO_{nt-1} + PA_{nt} \quad \forall n\ \forall t \quad (45)$$

As for the constraints regarding the inventory of a facility, it is defined in Equations (46) and (51). The ending inventory of a facility in a given period is equated to the sum of the inventory of the previous period and the production output of the current period, minus the transported amount from that facility.

$$LCO_{it} = LCO_{it-1} + PC_{it} - \sum_j OCP_{ijt} \quad \forall i\ \forall t \quad (46)$$
$$LPO_{jt} = LPO_{jt-1} + PP_{jt} - \sum_k OPE_{jkt} \quad \forall j\ \forall t \quad (47)$$
$$LEO_{it} = LEO_{it-1} + PE_{it} - [\sum_l OEF_{klt} + \sum_m OEB_{kmt} + \sum_n OEA_{knt}] \quad \forall k\ \forall t \quad (48)$$
$$LFO_{lt} = LFO_{lt-1} + PF_{lt} - [\sum_e OFB_{let} + \sum_f OFG_{lft}] \quad \forall l\ \forall t \quad (49)$$
$$LBO_{mt} = LBO_{mt-1} + PB_{mt} - \sum_g OBC_{mgt} \quad \forall m\ \forall t \quad (50)$$
$$LAO_{nt} = LAO_{nt-1} + PA_{nt} - \sum_h OAF_{nht} \quad \forall n\ \forall t \quad (51)$$

Equations (52) to (57) present the inventory constraints for the inputs of each facility per period. The input ending inventory in a facility for a given period is equated to the sum of the inventory of the previous period and the total deliveries received during the current period, minus the amount of inputs used in production in that facility.

$$LCI_{it} = LCI_{it-1} + [\sum_a OCC_{ait} + \sum_j OPC_{jit}] - [PC_{it} * YC] \quad \forall i\ \forall t \quad (52)$$
$$LPI_{jt} = LPI_{jt-1} + [\sum_b OPP_{bjt} + \sum_j OCP_{ijt}] - [PP_{jt} * YP] \quad \forall j\ \forall t \quad (53)$$
$$LEI_{it} = LEI_{it-1} + [\sum_c OEE_{ckt} + \sum_j OPE_{jkt}] - [PE_{kt} * YE] \quad \forall k\ \forall t \quad (54)$$
$$LFI_{lt} = LFI_{lt-1} + [\sum_d OFF_{dlt} + \sum_k OEF_{klt}] - [PF_{lt} * YF] \quad \forall l\ \forall t \quad (55)$$
$$LBI_{mt} = LBI_{mt-1} + \sum_k OEB_{kmt} - [PB_{mt} * YB] \quad \forall m\ \forall t \quad (56)$$
$$LAI_{nt} = LAI_{nt-1} + \sum_k OEA_{knt} - [PA_{nt} * YA] \quad \forall n\ \forall t \quad (57)$$

The relationship between the purchased material inputs from each supplier and the transported amount from supplier locations to their respective facilities are displayed in Equations (58) to (61). For the transport activities between each process facility, the relationships between the transported amount from source facilities to their respective destinations and the output inventory from each source facility are displayed in Equations (62) to (65).

$$OCC_{ait} = MC_{ait} \quad \forall a\ \forall i\ \forall t \quad (58)$$
$$OPP_{bjt} = MP_{bjt} \quad \forall b\ \forall j\ \forall t \quad (59)$$

$OEE_{ckt} = ME_{ckt} \quad \forall c\ \forall k\ \forall t$ (60)
$OFF_{dlt} = MF_{dlt} \quad \forall d\ \forall l\ \forall t$ (61)
$\sum_i OPC_{jit} \leq 0.4 * [PP_{jt} * YP] \quad \forall j\ \forall t$ (62)
$\sum_l OEF_{klt} \leq 0.6 * [LEO_{it-1} + PE_{it}] \quad \forall k\ \forall t$ (63)
$\sum_m OEB_{kmt} \leq 0.3 * [LEO_{it-1} + PE_{it}] \quad \forall k\ \forall t$ (64)
$\sum_n OEA_{knt} \leq 0.1 * [LEO_{it-1} + PE_{it}] \quad \forall k\ \forall t$ (65)

The equations regarding the relationships between the transported amount from process facilities to the customer locations and the output inventory from each process facility are displayed in Equations (66) to (67).

$\sum_e OFB_{let} \leq 0.9 * [LFO_{lt-1} + PF_{lt}] \quad \forall l\ \forall t$ (66)
$\sum_f OFG_{lft} \leq 0.1 * [LFO_{lt-1} + PF_{lt}] \quad \forall l\ \forall t$ (67)

Equation (68) indicates that the recovery for cultivation input is equal to the transported amount from the pretreatment facility to the cultivation facility. The relationship between the recovered material inputs in each facility and the respective material input usage in production for each facility is presented in Equations (69) to (71). Lastly, non-negativity, integer, and binary constraints are applied to relevant variables.

$RCI_{it} = \sum_j OPC_{jit} \quad \forall i\ \forall t$ (68)
$RPI_{jt} = 0.1 * [PP_{jt} * YP] \quad \forall j\ \forall t$ (69)
$REI_{kt} = 0.1 * [PE_{kt} * YE] \quad \forall k\ \forall t$ (70)
$RFI_{lt} = 0.1 * [PF_{lt} * YF] \quad \forall l\ \forall t$ (71)

5. Model Validation

The MILP model was validated using the CPLEX optimization solver in MATLAB R2019b. A study period of 10 years was chosen for the case study. Two potential locations are considered for the cultivation, extraction, and biochar processing facilities, the pretreatment and biorefinery input sources, and the glycerol and biochar customer sinks. For the pretreatment, biorefinery, and anaerobic digestion facilities, as well as the fertilizer customer locations, cultivation and extraction input sources, three potential locations are considered. As for the biodiesel customer sinks, four locations are included in the model. The superstructure supply chain network for the study is presented in Figure 2.

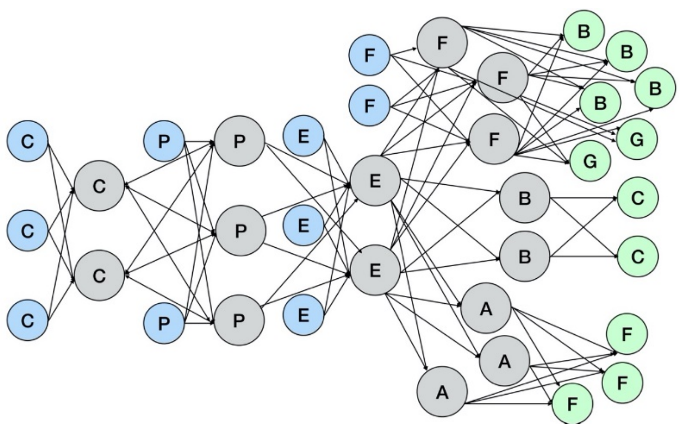

Figure 2. Superstructure Supply Chain Network

The model results are to be presented in three parts; the first two being the single objective optimization of profit and environmental impact respectively, and ending with the simultaneous optimization of the two objectives.

5.1 Profit Maximization

Looking into the maximization of profit as a single objective for optimization, results show that for the facilities that have three possible locations, only one or two are chosen as constructed facilities as shown in Figure 3. This is likely caused by the associated fixed costs of building each facility.

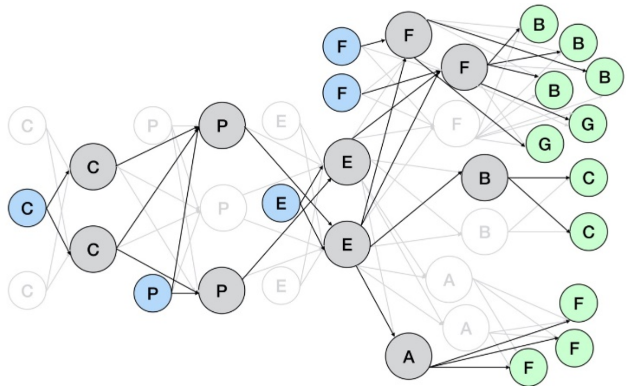

Figure 3. Supply Chain Network under Profit Maximization

Table 1 presents a summary of the results of the optimization model along with the optimal profit value. It is observed that the total product output of the network for the 10-year study period is equal to the overall capacity of the supply chain. This is because the model chooses to produce at maximum capacity, with a minimum number of facilities, to be able to generate the most revenue for the supply chain network.

Table 1. Results Summary for Impact Minimization

	Value
Profit (in USD)	1,688,662.84
Environmental Impact (in GHG)	23,847.82
Total Biodiesel Output (in kg)	2682
Total Glycerol Output (in kg)	298
Total Biochar Output (in kg)	900
Total Fertilizer Output (in kg)	300

5.2 Environmental Impact Minimization

Results for the impact minimization single objective optimization show that only one facility was constructed for cultivation as presented in Figure 4. This is because the cultivation process has been proven to be very energy extensive. Table 2 shows a summary of results of the optimization model along with the value for the optimal environmental impact.

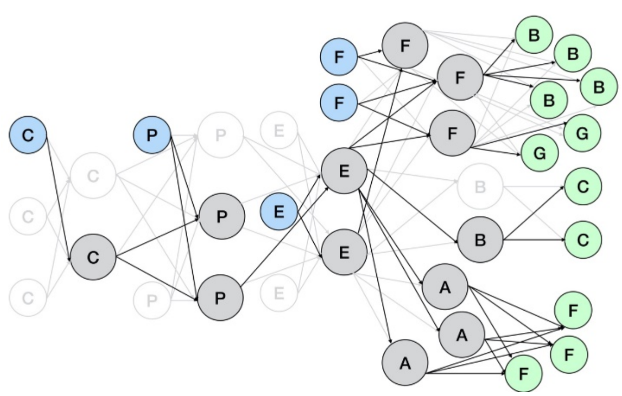

Figure 4. Supply Chain Network under Environmental Impact Minimization

Table 3 presents a summary of the results of the optimization model along with the optimal profit value. It is observed that the total product output of the network for the 10-year study period is equal to the overall capacity of the supply chain. This is because the model chooses to produce at maximum capacity, with a minimum number of facilities, to be able to generate the most revenue for the supply chain network.

Table 2. Results Summary for Impact Minimization

	Value
Profit (in USD)	-2,343,977.60
Environmental Impact (in GHG)	7,644.37
Total Biodiesel Output (in kg)	100
Total Glycerol Output (in kg)	100
Total Biochar Output (in kg)	100
Total Fertilizer Output (in kg)	100

As seen in Table 2, the overall output generated by the network equated to the declared demand for the model since the environmental impact is positively correlated with the outputs of each facility. Also, the supply chain network under minimized impact resulted to a profit loss for the 10-year study period. This is attributable to the establishment of multiple facilities while only catering to the minimum customer demand.

5.3 Multi-Objective Optimization

Making use of the obtained results from the first two optimization trials, which are displayed in Table 3, the simultaneous optimization of the profit and environmental impact objectives can be achieved which will result in the optimal supply chain network. The resulting profit from the profit maximization trial was declared as the best value while its corresponding impact was assumed to be the worst possible value. Likewise, the environmental impact obtained from impact minimization trial is set to be the best possible value while the profit for that scenario is assumed to be the worst.

Table 3. Best and Worst Possible Values for Profit and Impact

	Best	Worst
Profit (in USD)	1,688,662.84	-2,343,977.60
Environmental Impact (in GHG)	7,644.37	23,847.82

The optimal network for the simultaneous optimization for profit and environmental impact, presented in Figure 5, is much similar to the profit maximization result with regards to the construction of facilities. This is because the cultivation process has been proven to be very energy extensive.

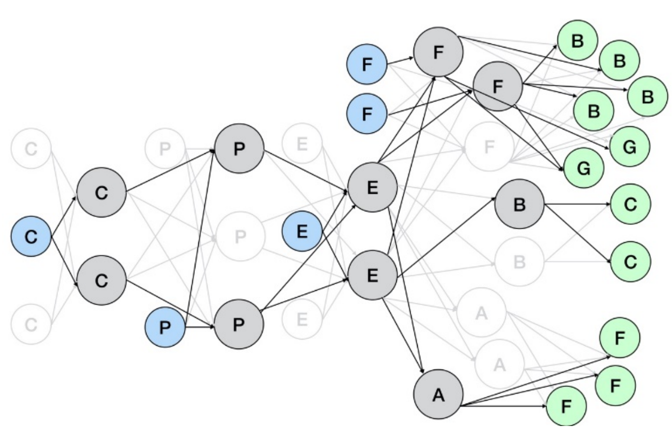

Figure 5. Optimal Supply Chain Network

As seen in Table 4, the overall output generated by the network differs very much from the results of the profit maximization trial unlike the resulting supply chain network. The profit and environmental impact values for this trial showed an improvement in the worst possible value, yet still being far off from its best. Nonetheless, the results show that a balance between the two objectives is indeed possible while still meeting demand and capacity constraints.

Table 4. Optimal Results Summary

	Value
Profit (in USD)	655,314.76
Environmental Impact (in GHG)	16,189.78
Efficiency	47.26%
Total Biodiesel Output (in kg)	1,854.1
Total Glycerol Output (in kg)	206.0087
Total Biochar Output (in kg)	629.8275
Total Fertilizer Output (in kg)	100

6. Conclusion and Recommendation

This study introduced a multi-objective optimization model for an algal biofuel supply chain incorporating resource recirculation aiming to maximize profit and minimize environmental impact. Having optimized the two objectives separately, displayed the tradeoffs that occur between the environmental and economic objectives. When profit is maximized, conflict is evident as the environmental impact increases. With the implementation of impact minimization, yields a net loss for the biofuel supply chain given that less revenue is generated due to lowered biofuel production. The consideration of both objectives in a multi-objective optimization model strikes a balance between the two objectives.

Future work may look into the incorporation of different methodologies to properly estimate the environmental impacts such as Life Cycle Analysis. Moreover, the incorporation of uncertain parameters into the optimization model such as demand, recovery rates, and process unit product yield is a possible extension for this research. Another extension to this research is looking into the effects of resource recirculation on the product quality of the supply chain through the constant reuse of material. Lastly, the use of real-life data for the estimation of parameters in the model would likely yield more appropriate results to be applied in real-world industry applications.

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