A scheduling and planning algorithm for microalgal cultivation and harvesting for biofuel production

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Abstract. Microalgae is highlighted as the most feasible bioenergy feedstock because it can produce high amounts of lipids, carbohydrates, and hydrogen, which are necessary compounds for the production of various biofuels, while only requiring minimal water and land due to high photosynthetic efficiency. However, there are technical limitations that negatively influence the mass production of biofuel from algae, making it economically infeasible on a commercial scale. One of these bottlenecks exists in its cultivation. The cultivation method and system are critical in determining the amount and quality of biofuel that may be generated from the microalgae. Additionally, the peak biomass concentration, and productivities for the different compounds and nutrients within microalgae do not occur at the same time. Hence, this work proposes a planning tool for microalgal cultivation systems that incorporates species selection, and cultivation and harvesting approach selection and scheduling, while balancing the minimization of environmental impact and maximization of profit realized. The capabilities of the proposed decision support model is demonstrated through a hypothetical case study. Scenario analyses is likewise conducted to establish an understanding of system behavior and performance over time and under various conditions. The results of the computational experiments show the tools capabilities in simultaneously considering algae growth rates and compound productivities in decision making, for instance biomass species that is able to generate the most of a certain high value fuel is prioritized in cultivation and harvesting.

Keywords: Microalgae, Biofuel production, Species selection, Cultivation, Scheduling

1. Introduction
A global energy crisis is expected to occur in the near future because of the accelerated increase in energy consumption worldwide coupled with diminishing fossil fuel resources [1]. Additionally, the sustainability of using fossil fuels as our primary energy source is an issue because of the environmental
and health hazards it poses to our community from greenhouse gas (GHG) emissions, such as climate change and global warming. In response, focus has been shifted towards using biomass as an alternative energy source to fossil fuels given that it releases net zero carbon emissions throughout its life cycle and its renewable properties [2].

Microalgae is highlighted as the most feasible bioenergy feedstock because it can produce high amounts of lipids, carbohydrates, hydrogen, which are necessary compounds for the production of various biofuels, while requiring minimal water and land due to high photosynthetic efficiency [3]. Several types of renewable biofuel may be produced from microalgae, namely biomethane, biohydrogen, biodiesel, biogas, and bioethanol [4]. Additionally, microalgae can supply biofuel throughout an entire year as oil yield cultivation of microalgae is not affected by seasonality. Microalgae can also eliminate carbon dioxide emissions from flue gases released from the thermochemical processing of fossil fuels [5].

However, there are technical limitations that negatively influence the mass production of biofuel from algae, making it economically infeasible. One of these bottlenecks exist in the cultivation of microalgae. There are two main types of cultivations systems for microalgae, the open and closed culture system. Although the open system cultivation is more practical and entails less investment costs [6], it has low productivity because of higher risk of contamination of other microalgal species and uncontrollable environment and weather variability [7]. On the other hand, closed system cultivation has higher biomass productivity because of the controlled environment of a photobioreactor system, but would require higher capital costs [6]. In addition, different species have different growth rates, cultivation requirements, and ranges of productivity for protein, lipids, and carbohydrates [8]. The microalgae species, cultivation method and system are critical in determining the final microalgae biomass productivity and its lipid, carbohydrates, and hydrogen yield, which undoubtedly impacts the amount and quality of biofuel that may be generated from the biomass [9]. These compounds cannot be sufficiently produced by microalgae under normal conditions, therefore the economic feasibility of microalgal biofuel production has not realized the stage for optimal commercial viability [4].

The complexity of planning and scheduling the cultivation system of microalgae for biofuel production requires a systematic approach to ensure that we can realize the most potential benefits, while minimizing the negative risks. Despite the importance of the cultivation stage of microalgae and the complexity of the decisions involved, no study has given specific focus on it. Existing optimization modeling studies excluded microalgae cultivation from their system boundary [10,11], considering only the downstream processes that make use of grown and harvested microalgae to produce biofuels and other high-valued co-products. A mathematical model has been proposed for tree species selection and planting scheduling in forestation projects [12], but there are several critical differences in tree and microalgae growth that requires a unique optimization model for this context. Hence, this work aims to develop a mathematically-based planning tool for microalgae cultivation systems that incorporates species selection, and cultivation and harvesting approach selection and scheduling, while balancing the minimization of environmental impact and maximization of profit realized. In particular, the model will determine the algae species and schedule for cultivation and harvesting that maximizes biofuel yield, which is dependent on biomass yield and the concentrations of lipids, carbohydrates, and hydrogen.

2. Model Formulation

The mixed-integer non-linear programming model for the microalgae cultivation system under study is given in equations (1) to (17). The developed model aims to make decisions on microalgae species selection, cultivation and harvesting approach and scheduling that simultaneously maximizes profit and carbon sequestration while satisfying various fuel demands and capacity constraints. Table 1 shows the relevant parameters and variables used in the model.

The two objectives of the model are to maximize profit \( P \) and carbon sequestration \( G \), which are inherently conflicting in nature. Goal programming approaches are useful in simultaneously optimizing two or more conflicting objectives because it ensures that the best Pareto optimal solution is achieved with minor computational effort [11]. A goal programming approach has previously been developed by [12], but their formulation is limited because it considers the performance of the model on achieving the two objectives on unequal scales. This issue was addressed by [11] and [2] through normalizing the
The total profit of the system is the net of revenues \( R_t \) less fixed \( F_t \) and variable \( V_t \) costs summed across all periods as in equation (2). Equation (3) defines revenues as the product between the unit contribution margin of a certain fuel type \( p_n \) and the amount of that fuel produced and sold. The fixed costs each period is described in equation (4) to be dependent on whether each of the cultivation and harvesting options are operating in a given period multiplied with their respective operating costs \( b_i \) and \( v_j \), while variable costs are incurred from purchasing samples of algae, given by the product between the purchasing price \( w_s \) and the amount of algae sample purchased, and the variable operating costs for conducting a certain harvesting technique, which may be obtained from the product between the total amount of algae to harvest and the corresponding cost of using the particular harvesting technique \( e_j \), as in equation (5). The second sub-objective of the system is to maximize the carbon sequestered from cultivating algae, which is dependent on the carbon sequestration rate influenced by the cultivation method and the species \( E_{si} \), and the amount being cultured each period as in equation (6).

\[
\begin{align*}
\text{max } & \text{min } \left[ z_G \left( \frac{p-p_{\text{min}}}{p_{\text{pot}}-p_{\text{min}}} \right), z_P \left( \frac{a-G_{\text{min}}}{a_{\text{pot}}-G_{\text{min}}} \right) \right] \\
p &= \sum_t (R_t - F_t - V_t) \\
R_t &= \sum_n p_n x_{nt} \quad \forall t \\
F_t &= \sum_i b_i a_{it} + \sum_j v_j f_{jt} \quad \forall t \\
V_t &= \sum_s w_s v_{st} + \sum_s \sum_t e_j q_{sijt} \quad \forall t \\
G &= \sum_s \sum_t E_{si} l_{sit} \\
\end{align*}
\]

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\end{align*}
\]

### Table 1. Parameters and decision variables.

| Notation | Definition |
|----------|------------|
| \( c_i \) | Capacity of cultivation medium \( i \) |
| \( h_j \) | Capacity of harvesting approach \( j \) |
| \( m_{si} \) | Minimum fraction of capacity to sustain growth of algae \( s \) in cultivation medium \( i \) |
| \( g_{sit} \) | Growth rate of algae species \( s \) when cultivating in medium \( i \) given by its age |
| \( H_{sn} \) | Amount of fuel type \( n \) that may be produced from each unit of algae \( s \) |
| \( v_{st} \) | Amount of algae of species \( s \) purchased for cultivation on period \( t \) |
| \( r_{sit} \) | Amount of algae of species \( s \) starting cultivation in medium \( i \) on period \( t \) |
| \( l_{sit} \) | Amount of algae of species \( s \) being cultivated in medium \( i \) on period \( t \) |
| \( q_{sijt} \) | Amount of algae of species \( s \) cultivated in \( i \) harvested using \( j \) on period \( t \) |
| \( u_{snt} \) | Amount of algae of species \( s \) converted into fuel type \( n \) on period \( t \) |
| \( x_{nt} \) | Amount of fuel \( n \) produced and sold on period \( t \) |
| \( f_{jt} \) | Binary variable, 1 if harvesting approach \( j \) is operating on period \( t \) |
| \( a_{it} \) | Binary variable, 1 if cultivation medium \( i \) is operating on period \( t \) |
| \( l_{sit} \) | Binary variable, 1 if algae of species \( s \) is cultivated in medium \( i \) on period \( t \) |

Objective values. Thus, this study proposes equation (1) to simultaneously optimize two weighted objectives as discussed in [1,2], but with the added consideration of weights, which are represented by the parameter \( z \) based on relative importance. This captures the various priorities or importance of the objectives during optimization. The model is prevented from sacrificing one objective for the benefit of the other and aims to achieve a balance between the two. This is done through maximizing the minimum between performance ratings, which are the quotient between the actual improvement realized (difference between the actual values and worst values) and the potential improvement (difference between potential and worst values). The potential values \( (P_{\text{pot}} \text{ and } G_{\text{pot}}) \) are obtained through maximizing that objective exclusively as a single objective optimization model, while the worst values \( (P_{\text{min}} \text{ and } G_{\text{min}}) \) are obtained when the other objective is solved solely.
\[ l_{sit} = \prod_d r_{sid}(1 + g_{sid}) - \sum_d \sum_j q_{sid, t-1} \quad \forall sit \]

where \( 1 \leq t' \leq d \leq t \) and \( g_{sid} = f(\text{age}_{t't}) \) (10)

\[ l_{sit} \geq m_{si} c_{it} \quad \forall sit \] (11)

\[ \sum_s l_{sit} \leq a_{it} c_i \quad \forall sit \] (12)

\[ \sum_s \sum_i q_{si, j} \leq f_{jt} h_j \quad \forall jt \] (13)

\[ \sum_i \sum_j q_{si, j} = \sum_n u_{snt} \quad \forall st \] (14)

\[ x_{nt} = \sum_s u_{snt} h_{sn} \quad \forall nt \] (15)

\[ r_{sit}, q_{si, j}, v_{st}, l_{sit}, u_{snt}, x_{nt} \geq 0 \quad \forall sjnt \] (16)

\[ l_{sit}, a_{it}, f_{jt} \in \{0, 1\} \quad \forall sjit \] (17)

Equation (7) defines the amount of a certain algae species to be purchased each period to be equal to the total algae of the same species to be cultivated in different mediums that period. The amount of algae that may be cultivated in a specific cultivation medium is limited by the medium’s capacity in equation (8), while equation (9) ensures that algae species cannot be mixed. The current amount of algae in a particular cultivation medium each period is described in equation (10) to be based on the initial algae placed in the medium for cultivation affected by its growth rate, which is a function of the algae’s age, less the amount of algae that has been harvested each period prior to the current. Equation (11) ensures the amount of algae left in each cultivation medium to be at least within a certain fraction of the medium’s capacity for sustainable growth. On the other hand, equation (12) limits the algae in each cultivation medium to its capacity. Equation (13) forces the amount of algae harvested each period to be within the capacity of the harvesting technology. The amount of algae of a particular species harvested on a particular period is allocated for the production of various fuel types in equation (14). Equation (15) describes the amount of fuel produced and sold each period to be based on the amount of algae converted to the particular fuel type and the corresponding conversion rate. Lastly, equation (16) and (17) applies non-negativity and binary constraints to the appropriate variables.

### 3. Computational Experiments

The model was validated through the linear solver CPLEX on the MATLAB software. The non-linear equations were linearized to facilitate this. The system understudy is composed of 3 algae species, 2 cultivation methods, 2 harvesting methods, and 3 fuel types considered across 5 time periods. Hypothetical values were used for the validation.

The potential and worst values for both objectives were obtained through optimizing each objective individually. This is equivalent to putting sole priority on each objective. For instance, optimizing the economic objective exclusively would mean that \( z_p = 1 \) and \( z_g = 0 \), while optimizing the environmental objective alone means that \( z_p = 0 \) and \( z_g = 1 \). Eleven sets of weights for both objectives were considered in increments of 0.1. A solution is obtained for each set of priorities to compare the trend of the profit and carbon sequestration and system behaviour. The results of the model validation which compares the trend of profit and carbon sequestration are shown in Figure 1.

It can be observed from figure 1 that the highest carbon sequestration may be achieved when the most priority is given to it, while the highest profit is obtained when it is solely prioritized. A decision-maker that prioritizes achieving the most carbon sequestration would maximize the amount of algae that are being cultivated in its different medium, and gives focuses on the closed photobioreactors instead of open raceway ponds because it is able to capture the most emissions. However, this significantly decreases the profit of the system because closed photobioreactors are more expensive to operate. Significant operating costs are racked up in this scenario as cultivation are operated every period to maximize carbon captured from the algae being cultivated.

On the other hand, when the decision-maker prioritizes maximizing profit solely, it focuses on purchasing and cultivating the cheapest algae that can be converted into the most high-value fuel. However, because emphasis is placed on producing and selling biofuel, the amount of algae that is kept in the cultivation media is not as high as they are harvested as quickly as possible. As a result, this scenario experiences a low performance on the carbon sequestration objective. The model validation
demonstrates the model’s ability to consider the growth rate of the algae, wherein it keeps algae in cultivation while the growth rate is still high but decides to harvest when the growth rate plateaus. With the use of the goal programming approach proposed in this study to handle the two conflicting objectives, a balance between the objectives can be achieved on different relative importance levels. Additionally, figure 1 indicates that the most favourable combinations for objective weightings may be found at 0.3 ≤ \( z_p \) ≤ 0.7 or 0.3 ≤ \( z_G \) ≤ 0.7 because it is at these points that the system achieves relatively high performances on both objectives evidenced by the small gaps between the red and blue lines in figure 1. Beyond these points, the less prioritized objectives takes a steep dive, while the prioritized objective only increases slightly.

4. Conclusion and Recommendations
A multi-objective optimization model was developed and proposed in this study as a planning tool for the cultivation and harvesting of algae for biofuel production, which has previously been excluded in the system boundaries of existing optimization models for microalgal-based biofuel production. Particularly, the model may be used by decision-makers and managers to guide species selection, selection of cultivation media and harvesting approaches, scheduling cultivation and harvesting of algae, as well as planning the production of various biofuels from the harvested algae, while capturing the varying growth of rate of algae as it grows and as affected by decisions on cultivation and harvesting techniques. The model is able to consider the biomass’ growth rate together with its productivity on different compounds, wherein it selects a particular microalgae species depending on the compounds that reaches the highest concentration and can produce the most valuable fuel. Moreover, the results of the computational experiment exhibit the model’s ability to determine the peak fuel yield based on biomass concentration and compound productivity. Additionally, the proposed tool captures weighted conflicting economic and environmental objectives simultaneously, ensuring that a balance is reached between the two using a goal programming approach. Model implementation demonstrate that the model achieves its objectives by making sure that algae yield is maximized to increase profit from biofuels, while the algae’s stay in cultivation is also prolonged to increase carbon sequestration. Algae cultivation is vulnerable to contamination risks that that could be unfavourable for its fitness as a biofuel feedstock; hence, extensions of this work may explore algae nutrients productivity and growth as uncertain parameters in a robust optimization model. Future work can also consider capacity and inventory planning decisions. Lastly, the model and its extensions should be applied to planning such systems on a commercial scale.
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