Multi-objective optimization of water exchanges between a wastewater treatment facility and algal biofuel production plant

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Abstract. Wastewater treatment facilities are known to process water by removing nutrients before being discharged into different water bodies or reused. Traditional treatment of wastewater, however, leads to the emission of greenhouse gases contributing to climate change and air pollution. Thus, there is a need to identify the optimal configuration of treatment processes wastewater, coming from different sources, have to go through to satisfy the output quality requirements of various disposal or reuse options, while minimizing costs and negative impact to the environment. In addition, microalgae cultivation is a treatment alternative for wastewater since it can remove metals, nutrients, and contaminants from wastewater, with the added benefit of carbon sequestration. The cultivated algae can then be converted to renewable energy. Despite the potential benefits that can be gained from integrating wastewater treatment facilities with microalgal biofuel production, no optimization study has considered this opportunity. Considering different wastewater inputs, the joint system would select the best treatment process for nutrient removal and cultivating algae, weighing the trade-offs in cultivating algae on different water mediums, the appropriate harvesting technique, and whether the water by-product should be sent back to the treatment facility for further processing, disposal, or reuse. The energy produced from the plant may either be sold or used to operate the two facilities. In this work, a novel multi-objective optimization model is developed to design economically and environmentally efficient integration of wastewater treatment facilities and microalgal biofuel production plants through water exchanges. A case study is solved to demonstrate the model’s decision on three different scenarios. In the objective of minimizing the costs, the model utilized the production of biofuels since it was subtracted from the expenses. As for minimizing carbon emissions, the model decided to operate the wastewater treatment plant since there were less processes used in the model. When goal programming was used in order to satisfy both objectives, the model found a balance between the two plants which in return chose the have some exchanges present.

Keywords: Microalgae, Greenhouse, Wastewater, Carbon Sequestration, Water Exchange
1. Introduction

Wastewater contains different impurities causing water pollution, which continuously puts the health of people at risk [1]. Wastewater treatment facilities alleviate these problems by removing nutrients such as phosphorus, nitrogen, and biochemical oxygen demand (BOD) present in wastewater before being discharged into different water bodies [2] or reused by people [3].

Traditional treatment of wastewater, however, leads to high emission of greenhouse gases into the atmosphere, which contributes to climate change and air pollution [4]. Moreover, economic feasibility remains a problem. There is a need to identify the optimal configuration of treatment processes while minimizing costs and negative impact on the environment.

Microalgae can be cultivated from the nutrients within the wastewater effluent [5,6]. Microalgae cultivation is a known treatment alternative for wastewater since it can purify contaminants present in the wastewater itself [7] while utilizing the cultivated algae by converting it into renewable energy that can be sold or used by the facilities [8]. Additionally, the cultivation of microalgae has the ability to sequester carbon emissions from the atmosphere, unlike other wastewater treatment processes that emit greenhouse gas emissions [5]. Nutrients for cultivation can come from various sources such as freshwater, saltwater, wastewater, or a mixture of mediums [9]. The growth rate and biomass productivity vary depending on the nutrients present in the cultivating medium [10]. Mixing water mediums may find a balance between toxicity and nutrient content [11].

Open and closed cultivation systems are the environments wherein microalgae are produced. Various factors including light illumination, carbon dioxide amount, water quantity, and nutrient content affect microalgae growth and biomass productivity [12]. After cultivation, microalgae are harvested from their respective mediums and used in the production of bioenergy. Common techniques used in microalgae harvesting are flocculation, flotation, and centrifugation wherein each technique differ in operational cost, cell count yield, quality of microalgae, and dewatering efficiency [13]. The water that exits the biofuel production plant may be disposed of immediately or returned to the wastewater treatment facility to be treated further [14].

Mathematical models have been designed that aimed at treating wastewater on both wastewater treatment plant and biofuel plant, respectively [3,15]. However, no optimization study has considered integrating the two facilities despite the potential benefits that can be gained from it. The proposed model is a network supply chain that connects the processes of a microalgal-based biofuel production plant and a wastewater treatment facility in producing their desired outputs. The model would help stakeholders decide whether to operate the two facilities symbiotically or treat the two independently depending on the results that would be generated in the model.

2. Model Formulation

The model formulation below includes the nomenclature, objective functions, and constraints.

| Indices | Definition                          | Parameters | Definition                          |
|---------|------------------------------------|------------|------------------------------------|
| i       | Input Type                         | B          | Biogas yield rate per cell count   |
| j       | Cultivation System                 | A_{mi}     | Contaminant value m of water input i |
| k       | Wastewater Treatment Process       | Q_{mj}     | Quality type m going through cultivation type j |
| m       | Quality Type                       | Ω_{mn}     | Quality type m going through harvesting method n |
| n       | Harvesting Technique               | X_{mk}     | Quality type m going through treatment process k |
| o       | Output Site                        | L_{jnm}    | Algal cultivation rate on quality type m on cultivation system j on harvesting option n |
2.1. Objective Function
The mathematical model ran using cost and environmental impact objectives individually. Afterwards, were combined using goal programming.

2.1.1. Cost
The cost objective function considers the operational cost per liter of water which will be incurred whenever a treatment process will be used. The cost of using freshwater for microalgae cultivation is also considered. Profit and savings coming from biofuel production are deducted from the cost objective.

\[
\text{Min } Z_p = \sum_j V_{Cj} \left( \sum_i V_{ij} V + \sum_k W_{kj} \right) + \sum_n V_{Hn} \left( \sum_j C_{jn} \right) + \sum_k V_{Pk} \left( \sum_n T_{nk} + U_{nk} + \sum_k P_{k/k} + \text{FW} \left( V_{1j} \right) - \text{PR}(B)(c) - \text{SW}(B)(c) - \text{SM}(B)(c) + d_1^+ - d_1^- \right)
\]

2.1.2. Environmental Impact
The environmental emissions brought by each treatment process are also considered in the model. The emissions vary depending on the volume of water entering each process.

\[
\text{Min } Z_e = \sum_j C_{Ej} \left( \sum_i V_{ij} \left( V + \sum_k W_{kj} \right) + \sum_n V_{Hn} \left( \sum_j C_{jn} \right) \right) + \sum_k V_{Pk} \left( \sum_n T_{nk} + U_{nk} + \sum_k P_{k/k} + \text{FW} \left( V_{1j} \right) \right) - \text{PR}(B)(c) - \text{SW}(B)(c) - \text{SM}(B)(c) + d_2^+ - d_2^- \]

2.1.3. Bi-Objective

In simultaneously optimizing the two objective components, goal programming approach was used in order to consider two conflicting objectives [16]. The positive deviations of each objective function were given a goal weight, and both are added.

$$\text{Min } Z = W_1 d_1^+ + W_2 d_2^+$$  \hspace{1cm} (3)

2.2. Constraints

The following equations show the constraints considered for the system.

2.2.1. Demand

The volume of wastewater that must be treated by the two facilities are shown in Equation 4. The model must treat the total demand of wastewater required in the system.

$$\sum_k U_{3k} + \sum_j V_{3j} \geq \text{DEM}_3$$ \hspace{1cm} (4)

2.2.2. Wastewater Treatment Plant

Equations 5 tackles the volume of water entering and exiting each process of the wastewater treatment plant. The capacity of water that each process can handle is shown in Equation 6. Equation 7 discusses the quality of water when it enters the treatment process.

$$(1-N_k)[\sum_n T_{nk} + U_{3k} + \sum_k P_{kkr}] = \sum_k P_{kkr} + \sum_j W_{kj} + \sum_o (Y_{ko}) (J_{ko}) \text{ } \forall k$$

$$\sum_n T_{nk} + U_{3k} + \sum_k P_{kkr} \leq \text{CAP}_k \text{ } \forall k$$  \hspace{1cm} (5)

$$\sum_k T_{nk} (\Omega_{mn}) + U_{3k}(\Delta_{mn}) + \sum_k P_{kkr}(X_{mk}) (I_{mk}) = X_{mk} (U_{3k} + \sum_n T_{nk} + \sum_k P_{krr}) \text{ } \forall mk$$

Where $k' < k$

Where $k'' > k$

2.2.3. Biorefinery

Equations 8 and 9 discusses the volume flow of cultivation system and harvesting, respectively. The capacity of each cultivation system in seen on equation 10. The quality of mixed water entering the cultivation system is shown in equation 11 and the quality after the harvesting operation is shown in equation 12.

$$\sum_i V_{ij} + \sum_k W_{kj} = \sum_n C_{jn} \text{ } \forall j$$  \hspace{1cm} (8)

$$(1-F_n) \sum_j C_{jn} = \sum_k T_{nk} + \sum_o H_{no} \text{ } \forall n$$  \hspace{1cm} (9)

$$\sum_i V_{ij} + \sum_k W_{kj} \leq \text{CAP}_j \text{ } \forall j$$  \hspace{1cm} (10)

$$\sum_k W_{kj} [(X_{mk})(I_{mk})] + \sum_i V_{ij} (A_{mi}) \geq Q_{mj} (\sum_i V_{ij} + \sum_k W_{kj}) \text{ } \forall mj$$  \hspace{1cm} (11)

$$\sum_j (C_{jn})(Q_{mj})(G_{mj}) \geq \Omega_{mn} \text{ } \forall mn$$  \hspace{1cm} (12)

2.2.4. Cell Count Yield

Equation 13 deals with the cell count obtained after going through cultivation and harvesting phase to be converted into biofuel.

$$\sum_j \sum_n \Omega_{mn}[(C_{jn})(Q_{mj})(L_{jnm})] = 3c$$  \hspace{1cm} (13)

2.2.5. Water Quality Requirement

Equations 14 and 15 are concerned with the water quality requirement that the water input must satisfy before disposal.

$$X_{mk} (I_{mk}) \leq R_{mo} (Y_{ko}) + M(1-Y_{ko}) \text{ } \forall mko$$  \hspace{1cm} (14)

$$\Omega_{mn} \leq R_{mo} (Y_{no}) + M(1-Y_{no}) \text{ } \forall mno$$  \hspace{1cm} (15)

2.2.6. Disposal Site Capacity

The capacity that each disposal site can handle is shown in Equation 16.

$$\sum_k Y_{ko} (1-N_k) (J_{ko}) + \sum_n H_{no} (Y_{no}) (1-F_n) \leq D_o \text{ } \forall o$$  \hspace{1cm} (16)

3. Model Validation

Computational studies were accomplished using Lindo Systems What'sBest! Solver Excel Add-in on a Razer Blade Advanced 2019 with a 2.20 GHz Intel Core i7 processor and 16GB of RAM. Wastewater
treatment plant input parameters from [3], and hypothetical values for cultivation parameters were used in validating the proposed model.

The model was first minimized in terms of cost and carbon emissions individually to achieve the best possible value for each objective component. Goal programming is done afterward to determine if there are solutions that can give a balance in the tradeoff between the two objective functions. This gives flexibility in achieving the desired target output for the system. The values of the objectives for each run are displayed in Table 2.

| Table 2. Summary of Optimal Objective Values |
|---------------------------------------------|
| Potential | Minimizing Cost | Minimizing Emissions | Complete Model Run |
| Cost (PHP) | Goal Weight | Goal Weight | Goal Weight |
| 408,333.33 | 1 | 1,450,000 | 0 | 444,150.33 | 0.6 |
| Emission (mg) | 40,000 | 41,500 | 0 | 40,000 | 1 | 41,247.47 | 0.4 |

In consideration of the cost component only, the model was able to minimize the cost giving it a value of PHP 408,333.33. The model selected the algal biofuel plant exclusively in treating wastewater. The wastewater went through a closed cultivation system and is harvested using sedimentation option. The biofuel plant was used since it has the capability to convert microalgae cells into biofuel that gave additional profit when sold. Closed system was selected since it incurs lower unit cost while sedimentation was used due to its high cell count yield which are converted to biomass and sold. Both disposal sites had the same requirements in accommodating treated wastewater for disposal. For this run, only disposal site 2 was utilized. As seen, the model utilized entirely the production of biofuels through the algae since the profit was subtracted from the costs, which in return, could contribute greatly in minimizing the objective function.

On the other hand, wastewater treatment process, particularly tertiary treatment, was utilized when carbon emission was minimized solely. This gives a carbon emission value of 40,000 mg. In the system, tertiary treatment process provided the lowest carbon emission. The capacity of the treatment process exceeds the demand of wastewater and the quality improvement was enough for it to pass through that treatment process only in reaching the quality requirements before being discharged. Then disposal site 2 was also used to accommodate the processed wastewater. Based on the solution, the model decided to utilize the wastewater treatment plant only since there is a possibility of creating more carbon emissions when trying to produce algae since it may go more operations and processes. However, these two cases can still vary based on the parameters and resources present in the actual scenario.

When minimizing the two objectives simultaneously with 0.6 goal weight for cost and 0.4 for emission, both facilities are utilized. This yields a value of PHP 444,150.33 for cost and 41,247.47 mg for emission. All treatment processes were necessary in the wastewater facility while closed system was used system for microalgae cultivation since it is cheaper and gave enough improvement in the water quality. Then sedimentation method is still used in harvesting the cells for further conversion to biofuel. Wastewater moves through different processes in the treatment plant and biofuel plant to balance the cost and emissions acquired in the system. Both disposal sites were used in handling the treated wastewater.

4. Conclusions and Recommendations
A multi-objective optimization model integrating wastewater treatment facility and micro-algal biofuel plant that selects operational decisions in treating wastewater and cultivation of microalgae for biofuel
production was developed in this study. Goal programming was used in minimizing both operating costs and carbon emissions to provide flexibility in achieving the optimal solution for the conflicting objectives. Then scenario analysis was done to show the capability of the model. Results showed various combinations of processes should be used to treat wastewater depending on the weight assigned to each objective component. In minimizing the costs, the model utilized the production of biofuels since it was subtracted from the expenses. As for minimizing carbon emissions, the model chose to operate the wastewater treatment plant since there were less operations present in the model. When goal programming was used in order to satisfy both objectives, the model found a balance between the two plants which in return chose the have some exchanges present. Water treatment companies, engineers, and several other stakeholders may find the proposed model useful in acquiring the optimal strategy to be used in treating wastewater given that these two facilities exist. Moreover, stakeholders are given the choice to alter the goal weight of each objective depending on what they want to focus on. Future work should consider extending the scope of the system in a multi-period horizon. This would encompass the investment cost of building the facility and the variations on the demand for wastewater needed for treatment on different time horizons.

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