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# Holistic Modeling of Microalgae for Powering Residential Communities

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**Abstract**

An algae-based closed-loop system in a sustainable residential community that integrates waste stream management with energy generation is modeled. The sustainable material and energy cycle of microalgae for a residential building community is analyzed by schematic flow diagrams. A process simulation model for this integrated system is developed to evaluate the sustainability of the conceptual algae-based closed-loop residential community using system dynamics. The model reveals that this smart self-sustainable pattern through waste-to-energy microalgae technology - anaerobic digestion and renewable energy crops – can achieve sustainability in providing treated water, fertilizer, animal feed and energy for use, as well as reducing waste water emissions, resource consumption and environmental impacts in waste management.


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*Keywords:* microalgae, closed-loop, residential community, system dynamics

## 1. Introduction

In rural settings, many households are off the grid and use small package treatment plants or individual septic systems. Many low-density communities with less than 10,000 residents are not connected to public wastewater infrastructure and would need alternative systems. Microalgae are photo induced cell factories that transform $CO_2$ to potential biofuels, foods, and feeds. Microalgae have been identified as a promising

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renewable energy since they feature many benefits (e.g. high output, lipid buildup, capacity to grow on wastewater, recycle and recapture of waste nutrients, reuse of $CO_2$ from flue gas ) [1]. Microalgae use sunlight to produce oils, with a higher photosynthetic efficiency (ranging from 3% to 8%) than crop plants (0.5%) [2]. Furthermore, algae-based fuel is carbon-neutral, as algae assimilate similar amounts of $_{CO2}$ for its growth as is released upon fuel combustion [3]. There are acute environmental risks when releasing municipal wastewater that contains a high content of organic compounds and inorganic chemicals (e.g., phosphates, nitrates). The culture of the microalgae offers a dual benefit of treatment of wastewater and low cost culture of microalgae thus saving on the nutrient dose [5]. Microalgae that grow on anaerobically digested dairy manure wastewater environments are simultaneously a prospective economical source of liquid biofuels and also offer a high removal of dissolved nutrients [6]. In rural residential environments microalgae can provide local and biologically-produced clean renewable energy, which could result in a potential dramatic change in sustainable residential living.

Sustainable buildings involve strategies to minimize the need for energy and resource use, and to adopt renewable energy. To meet such strategy, current sustainable residential community living will need to shift to renewable energy, reuse and recycling of waste streams to reduce natural resource utilization and environmental impact. Microalgae can produce large quantities of biomass and oil, which can be converted to biodiesel. Previous studies are recognizing microalgae as a renewable and sustainable energy of promising potential [3, 4, 5, 7, 8, 9-13].

## 2. Waste stream management and sustainable living

The process workflow diagram for the algae-based sustainable biofuel production from wastewater is shown in Figure 1. In a high rate algal pond, the algae, water and nutrients circulate with paddlewheels, and the shallow pond allows for a better penetration of sunlight. The algae pond is fed with wastewater and produces treated water and mature algae. Collected treated water can be redirected to the pond or used for grassland, anaerobic digestion, or aquaculture production. Microalgae can be harvested daily, and the free water is removed through flocculation, centrifugation, vacuum belt dryers, or solar driers. The dried biomass is pulverized with a mortar and pestle before the oil is obtained

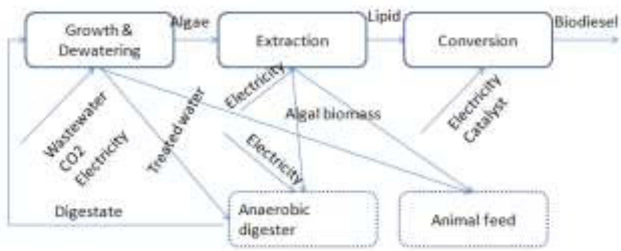


Fig. 1. Algae-based biofuel production from wastewater resources

### 2.1. System dynamics

System Dynamics (SD) is a thinking model and simulation methodology that was specifically intended to assist the study of dynamic behavior in complex systems. It operates in a whole-system approach and is a robust methodology when considering sustainability subjects [14]. SD is also a useful tool to study the interactions between natural resources, technology, economic and ecological sections.

Models represent systems, and Stella is modeling software that models a system with stocks, flows, converters and information flows [15]. The system under study in this paper is made up of several interacting dynamic production processes that feature resource and energy feedbacks. An integrated algae-based residential closed-loop SD assessment model using Stella is presented in Figure 2. In the system, energy for use comes from two sources: biodiesel energy and gas energy. Biodiesel energy is produced from the microalgae-biodiesel process. Gas energy is produced by biogas from the anaerobic digestion. A part of the energy for use will be offset in the steps of production processes, the rest will be used for domestic living. The water inflow into the pond includes wastewater, recycled water, water in digestate, and rain running into the pond, subtracting the evaporation from the pond surface. After the harvest of microalgae, some of the treated water will be recycled in the microalgae pond, while some will be used by the anaerobic digestor. In addition, some of the treated water meeting environmental emission requirements will be discharged into the environment. The amount of water recycled into the pond is determined by the difference between the pond volume and the wastewater inflow. The pond is assumed to be 0.3 meters (m) deep.

*2.2. Model input and output*

The model shown in Figure 2 consists of 12 stocks (units are shown in parenthesis): treated water (Kg), discharged water (Kg), algae stock (g), algae lipid (g), biodiesel (g), exaction biomass (Kg), animal feed (Kg), anaerobic digestion mass (Kg), biogas (m3), CO2 stock(m3), fertilizer(Kg) and energy for use (MJ).

The model features several converters with values ranging from 0 to 1: Kanaerobic percent, Kfeedpercent, Klipid content percent, KCO2 percent, KProductivity, and CO2 absorption coefficient. If Converter Kanaerobic percent is equal to 1, it means that the entire produced algae will be used for anaerobic digestion and not for lipid production. if the value is 0, it means that the residual mass will be used for anaerobic digestion, after all lipid production. Converter Kfeedpercent represents the percentage of algal biomass used for animal feed. Converters Klipid content percent and KCO2 percent denote the percentage of lipid content and CO2 in algae and biogas. KProductivity is the efficiency coefficient of algae production compared to the optimum possible production. Converter CO2 absorption coefficient is the ratio of absorbed CO2 by the microalgae to the gas sparged.

*2.3. Model description*

In the system, energy for use comes from two sources: biodiesel energy and gas energy. Biodiesel energy is produced from the microalgae-biodiesel process. Gas energy is produced by biogas from the anaerobic digestion. A part of the energy for use will be offset in the steps of production processes, the rest will be used for domestic living. The real algal production is determined by equation (1):

$$algaeproduction = P_{max} * K_{productivity} * area \qquad (1)$$

Where $P_{max}$ is the maximum algae production rate. $K_{productivity}$ is the efficiency coefficient of algae production compared to the optimum possible production.

The algae used for lipid production is:

$$lipidproduction = algaestock * (1 - Kanaerobic\ percent) \quad (2)$$

The generated lipid is calculated as:

$$lipidproduced = lipidproduction * Klipid\ content\ percent \quad (3)$$

In the microalgae-to-biodiesel process, the amount of energy consumed is represented as:

$$bioproductionenergy = growth\&dewaterenergy + extractionenergy + conversionenergy \quad (4)$$

The mass for anaerobic digestion originates from two sources: solid waste inflow and extraction biomass digestor inflow.

The entire algal biomass and the residual biomass after oil extraction can be used for animal feed and for biogas production. The amount of animal feed can be calculated from Eqs. (5-8):

$$anaerobicproduction = algaestock * Kanaerobic\ percent \quad (5)$$

$$biomassproduced = anaerobicproduction + lipidproduction * (1 - Klipid\ content\ percent) \quad (6)$$

$$feedinflow = extractionbiomass * Kfeed\ percent \quad (7)$$

$$animalfeed = animalfeed(0) + \int [feedinflow]dt \quad (8)$$

*2.4. Simulation results and discussion*

Results of the simulation reveal that with this integrated algae-based closed-loop residential community system, municipal wastewater and solid waste including livestock manure and domestic solid waste inflow will be turned into animal feed, fertilizer, treated water and energy for living use.

This system will be environmental-friendly in reducing wastewater and solid waste emission, producing renewable energy. Land use for microalgae growth should also be considered when environmental impact is assessed.

To achieve positive energy balance of the whole system, such aspects as selecting high lipid content percent algae strains, optimizing production systems to reduce the energy consumed in the microalgae-to-biodiesel and anaerobic digestion process, collecting animal manure and more organic MSW for anaerobic digestion will need to be addressed.

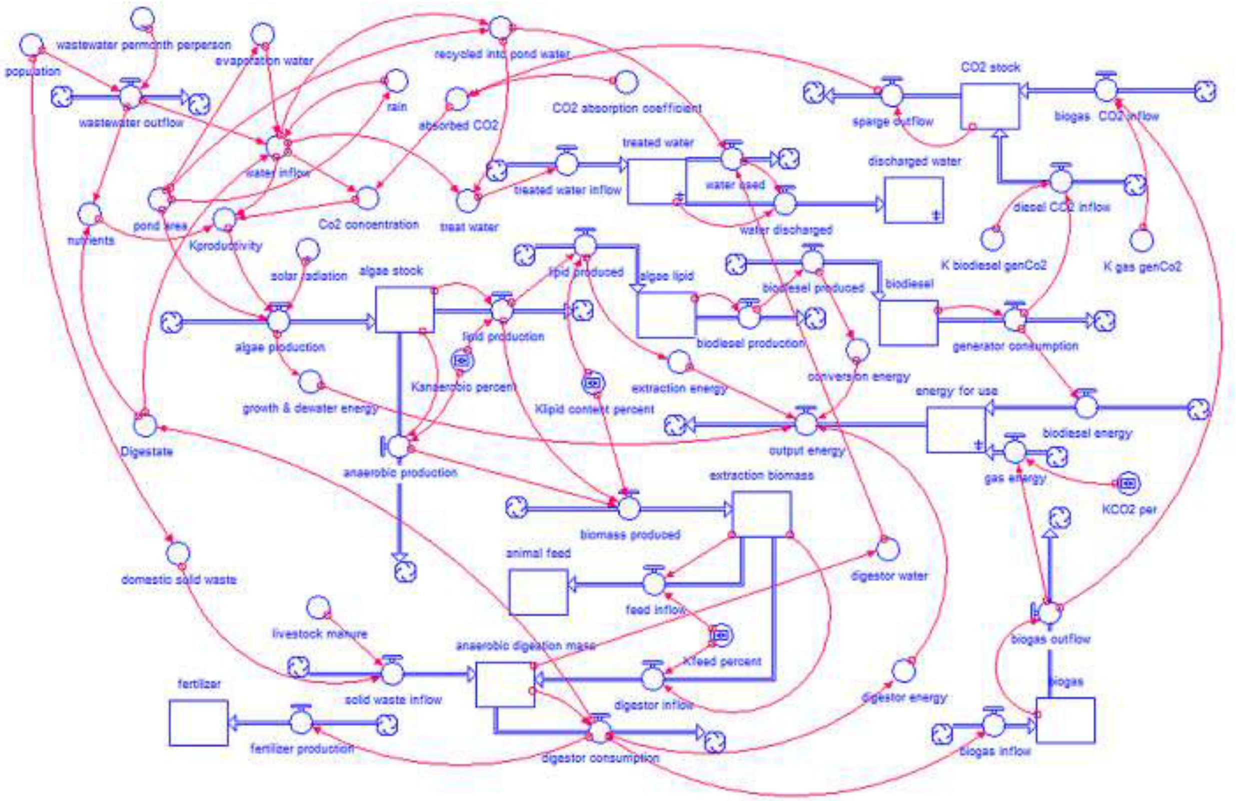


Fig. 2. SD model of microalgae for residential community

## 3. Conclusions

The residential community presents a self-sustainable pattern in which waste streams are recycled and reused to generate useful resources through waste-to-energy microalgae technology, including anaerobic digestion and renewable energy crops. Municipal wastewater, municipal solid waste and animal manure will lead to environmental quality degradation if not well treated in a cost effective manner. With these waste streams and solar radiation as input, the integrated algae system can produce feed, fertilizer, treated water and energy for community, reduce resource consumption and environmental impacts in waste management, and become efficient on the reduction of cost and emissions through innovative nutrient flow cycle and process design.

This research presents the SD model of an algae-based closed-loop system for this residential community. It can be used to evaluate the environmental impact and energy efficiency of this sustainable residential community in a holistic framework.

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**Biography**

Daniel Castro-Lacouture is Professor and Chair in the School of Building Construction at Georgia Institute of Technology. His current research centers on defining and implementing performance evaluation protocols for technology innovation in the built environment, such as sustainable construction materials and alternative sources of energy.