THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

A SYSTEMATIC CARBON AND ENERGY BALANCE OF THE PENN STATE ECO-MACHINE™ AND THE IMPLEMENTATION OF A VERTICAL FARMING SYSTEM TO INCREASE DUCKWEED PRODUCTION

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ABSTRACT

Due to the changing climate, the demand for environmentally friendly methods that maintain societal standards grows in importance. The Penn State Eco-Machine™ is an example of an alternative method to conventional wastewater treatment that decreases environmental impacts. A variety of microorganisms, macroinvertebrates, algae, and plants contribute to the treatment of wastewater and the storage of carbon and nutrients in the Eco-Machine™ with theoretically little energy input. However, an in-depth analysis of the system's net carbon and energy yields has not been systematically performed to evaluate its true environmental footprint relative to conventional methods.

In this study, carbon and energy balances were performed on each step of the Eco-Machine™ system. Carbon storage from biosynthesis and carbon release from respiration were determined using laboratory measurements and theoretical calculations. It was determined that the biological carbon uptake is higher than the wastewater-derived carbon influx, resulting in a net-carbon accumulation in the system. Similarly, the energy consumption of each mechanical component, and the theoretical energy production by renewable resources, were calculated. It was determined that the solar array was able to provide enough energy to meet electrical components required for operation of the Eco-Machine™, with heating requirements met by supplemental propane. By analyzing the resulting data sets, several opportunities to improve the overall sustainability of the system arose, such as sealing leaks in the greenhouse structure, increasing the air compressor efficiency, and maximizing the yield of plant biomass that can be used for the production of beneficial byproducts like fertilizer, fodder, and biofuels. In particular, the production of duckweed, a floating aquatic plant with a high growth rate, was noted as underutilized.

Although the Penn State Eco-Machine™ was not originally designed to maximize duckweed yield, a pilot-scale vertical farming system was constructed and monitored for several months as part of this study to determine if significant improvements to the system's carbon and energy balance could be achieved. With current lighting technology, the energy required to power the vertical farming system was found to be higher than the resulting energy that could be produced from duckweed-derived biofuels (ex., ethanol and methane); however, the protein-rich duckweed can be utilized in sustainable agriculture to increase the favorable impact the Eco-Machine™ has on the local bioeconomy. The addition of a larger scale vertical farming system could provide a greater increase in duckweed yield from the Eco-Machine™. Particularly in geographic regions which do not require heating, Eco-Machines™ are a promising alternative wastewater treatment method that can provide beneficial byproducts to support sustainable agriculture.

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1.0 Introduction

1.1 Background

In a time in which the environment is increasingly affected by man-made industry, innovative, environmentally conscious methods that maintain societal standards are imperative. In the wastewater industry, ecological wastewater treatment facilities can decrease the carbon footprint compared to conventional domestic wastewater treatment methods, if maintained and operated properly. Energy consumption can be limited when implementing ecological treatment systems at a large scale, especially in tropical and warmer temperate regions. Penn State's Eco-Machine™ is a pilot-scale example of a facility that can treat wastewater without any additive chemicals and can minimize waste from the process via ecological methods.

Conventional wastewater treatment plant (WWTP) methodologies do not typically address carbon and energy emissions nearly to the extent of a treatment facility like the Eco-Machine™. Although many conventional WWTPs capture methane from anaerobic digestion and use it for heat production, other plants still burn excess methane and release the resultant carbon dioxide into the atmosphere. Most do not have measures to counter the carbon emissions by installing carbon-negative systems like greenhouses. Carbon-negative systems are meant to extract more carbon out of the atmosphere than is released. The Eco-Machine™ greenhouse allows for constant perennial plant growth to decrease carbon dioxide emissions from the system. This method is the forefront of treating wastewater ecologically to prevent further contributions to climate change, and perhaps even contribute to drawdown.

1.2 Purpose and Significance

The purpose of this honors thesis is to complete a carbon and energy mass balance on the Penn State Eco-Machine™, a pilot-scale ecological wastewater treatment facility. Studies have found that water and wastewater industry could be contributing as much as 3% to total energy consumption in the United States (Burton, 1996). The Intergovernmental Panel on Climate Change (IPCC) determined the waste and wastewater industry contributes 2.8% to greenhouse emissions (2007). Implementing environmentally-conscious wastewater treatment technologies could decrease greenhouse gas emissions by the wastewater industry to a nominal amount.

1.3 The Penn State Eco-Machine™

The Penn State Eco-Machine™ has the capability to treat wastewater at a rate of 1000 gallons per day (GPD). However, to reduce the number of wastewater deliveries the facility must receive on a weekly basis, the Eco-Machine™ normally treats wastewater at 700 GPD. Wastewater from the Penn State WWTP that has passed through the primary clarifier is delivered by truck to the facility approximately twice per week. The Eco-Machine™ system begins in an underground 3000-gallon holding tank located adjacent to the greenhouse. The wastewater is pumped from this holding tank into the greenhouse, where it first passes through a 450-gallon closed anaerobic tank (CA1) followed by a 450-gallon closed anoxic tank (CA2), both with a diameter of 48”. In these tanks, microorganisms break down complex carbon compounds into alcohols and fatty acids, along with carbon dioxide and methane. Methanotrophs consume methane created by anaerobes, thus providing a holistic system that reduces methane emissions to below detection. CA2 receives wastewater containing nitrate from a recycle line further in the process, allowing for bacteria and microorganisms to convert nitrate into nitrogen gas through denitrification.

Three open aerobic tanks (OA1, OA2, and OA3), all 1000 gallons with a 67.5" diameter, oxidize ammonia and ammonium into nitrate through the process of nitrification. OA1 and OA2 are supplied with oxygen from air compressors that operate in cycles to produce a total of 8 hours of aeration per day. Aerobes are the primary mechanism for nitrogen, phosphorous, and chemical oxygen demand (COD) removal in the open aerobic tanks. In OA1 and OA2, there are floating islands planted with black magic taro (*Colocasia esculenta*) that help remove COD from the wastewater and are also excellent for removing nitrogen and phosphorous. The floating islands are 48-inch diameter styrofoam rings embedded with coconut coir fibers. Each supports a colony of taro that extend through the island and into the wastewater. The roots of the taro provide submerged surface area to support microbial biofilm.

In OA3, duckweed (previously identified as a co-culture of *Lemna japonica/minor* and *Wolffia columbiana* (Calicioglu and Brennan, 2018)) is grown to continue treatment. Duckweed is a floating aquatic plant which excels at removing nitrogen and phosphorous. With a fast growth rate and a high starch and protein content, harvested duckweed can be used as a feedstock for biofuel production or sustainable agriculture. OA3 is also the location of an internal recycle line, normally operating at a 50% recycle rate, which provides nitrate-rich wastewater to CA2 for denitrification. Photographs of duckweed at the Penn State Eco-Machine™ can be seen in Figures A2 through A4 in Appendix A.

The clarifier in the rear of the greenhouse allows sludge to settle and lets surface water continue, via a weir, to the subsurface constructed wetland on the floor of the greenhouse. Settled wastewater in the clarifier is recycled into the holding tank typically at 50% of the influent flow rate to maximize treatment effectiveness. A baffle near the weir prevents short circuiting in the clarifier and prevents duckweed present on the surface of the clarifier from exiting the tank.

Clarified wastewater proceeds into the constructed wetland (the gravel floor) from the back of the greenhouse near the clarifier towards the front door to further treat the water. The constructed wetland is approximately 560 ft^2 (52.0 m^2) and 2 feet deep and covers the entire interior floor area of the greenhouse. Numerous plants are present in the wetland to help treat the wastewater. Canna lily (*Roi humbert*), a plant known for its ability to treat wastewater in wetlands, is planted near the pond. Water canna (*Thalia dealbata*) is planted adjacent to the canna lily and can also be found along the wall of the open aerobic tanks. In five locations throughout the greenhouse, calla lily (*Zantedeschia aethipica*) can be found growing in dense but small areas. Images of these wetland plants can be found in Appendix A.

After passing through the wetland, water is collected into a pipe and transferred to the pond. While ponds are not a necessary step in the treatment process, the pond is meant to exhibit the water's cleanliness before being released. There are plans to construct an aquaponics system in the future that can also positively contribute to the carbon balance and the self sustainably of the Eco-Machine™. Figures 1 and 2 below give details on the systematic cross section described above and a plan view layout, respectively.

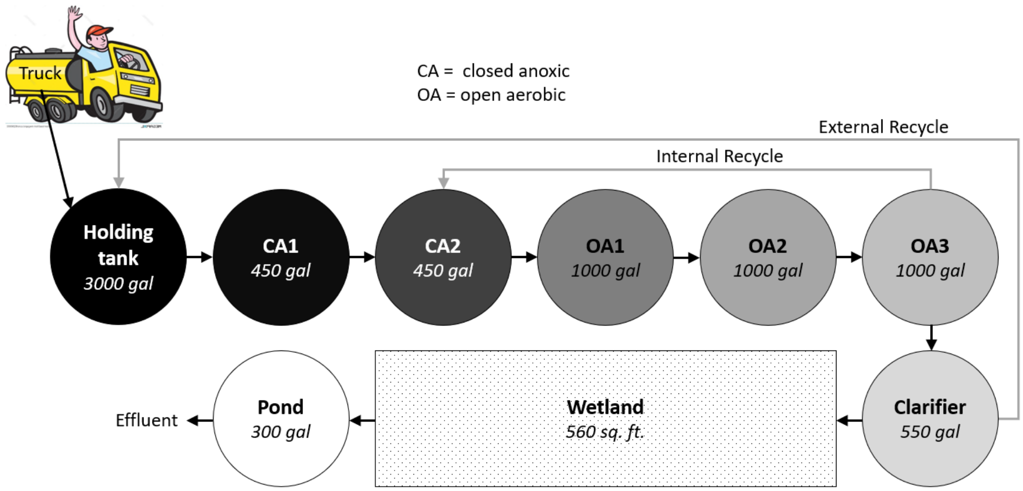

Figure 1: Penn State Eco-Machine™ schematic.

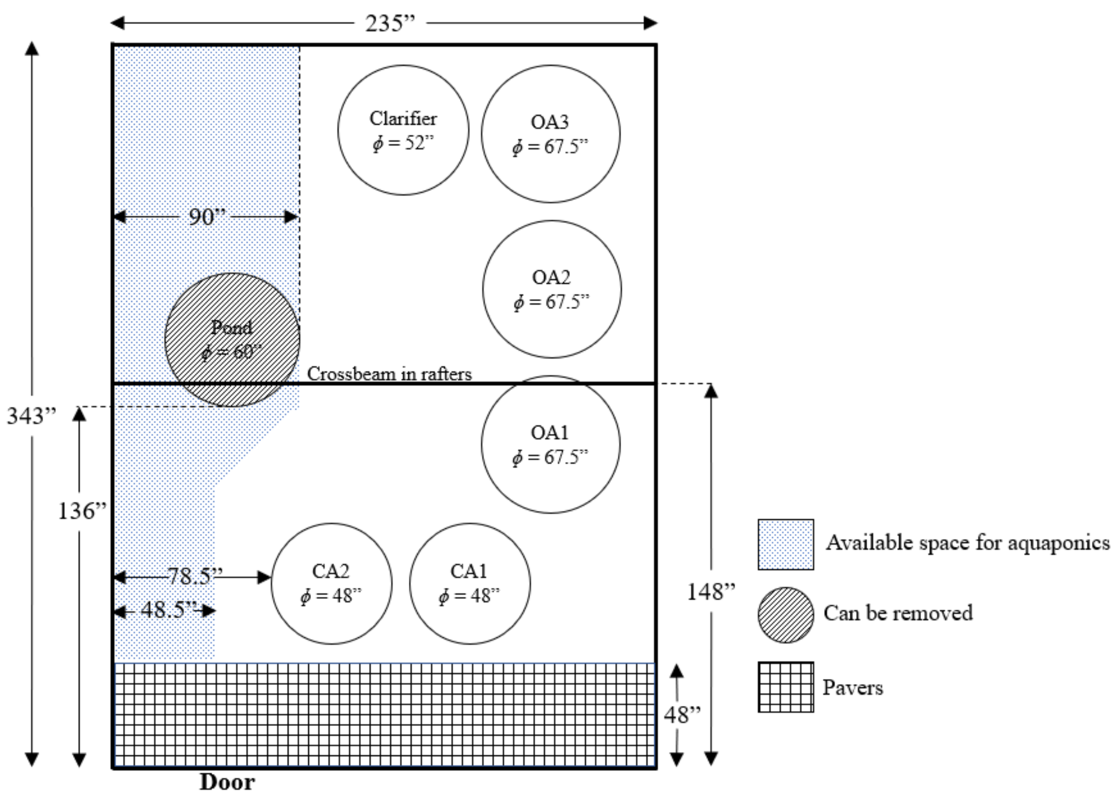

Figure 2: Penn State Eco-Machine™ plan view.

2.0 Energy Mass Balance

The purpose of this chapter is to understand the energy efficiency of the Penn State Eco-Machine™, determining its ability to be self-reliant on energy, and the validity of potential avenues of energy production by duckweed. Duckweed is a byproduct of the system proven to be an effective biofuel (Calicioglu and Brennan, 2018). It is also important to analyze the components of the Eco-Machine™ that require the most energy for proper operation and to recommend opportunities for improvement.

2.1 Energy Production

The Eco-Machine's™ primary source of energy production is a collection of photovoltaic (PV) solar panels located adjacent to the greenhouse and is mounted on a one-axis solar tracking system. The array consists of ten 175W panels (1.75kW in total), the output of which can be increased up to 25-30% with proper operation of the tracking system and maintenance/cleaning of the panels (Marion and Wilcox, 2020). The solar panels transfer energy to a Xantrex PV power inverter located inside the greenhouse. The other potential source of energy is duckweed, which can be used as a feedstock for biofuel production due to its high starch content. In the past, duckweed has been harvested from the system and tested for conversion into ethanol and methane in the laboratory (Calicioglu and Brennan, 2018).

2.1.1 Solar Panels

The solar panels contribute enough energy to run the entire system excluding heating since the furnace is powered by propane. However, the extent of energy production has never been documented. Using Equation 2.1 below, the theoretical solar energy yield can be calculated.

$$E\left(\frac{kWh}{yr}\right) = P_{max}\,(kW) * \frac{Solar\left(\frac{kWh}{m^2 * day}\right)}{1\,\frac{kW}{m^2}} * 365\left(\frac{days}{yr}\right) * DF \qquad \text{(E2.1)}$$

Solar = Average daily incident solar radiation on a one-axis tracking array

DF = Derating factor = 0.80 - 0.85 (in general)

P_{max} = Power rating = 1.75 kW

DF will be taken as 0.80 for conservative purposes in this study. Solar is divided by 1 kW/m^2 because it is the value of solar radiation intensity at which the panels are rated. Solar rating is determined by location, and it can vary depending on the solar panel tilt. On November 15, 2018, the tilt was at -29˚ from the horizontal, which favors the summer sun. According to the National Renewable Energy Laboratory (NREL), the average annual solar of a one-axis tilt at a latitude -15˚ is 5.2 kWh/yr for Williamsport, PA, which is the closest documented location to State College (Marion and Wilcox, 1992). At a latitude of -15˚, productivity is highest during the direct sunlight of the summer and is lowest during the winter. Figure 3 depicts the average daily solar energy yield in Williamsport each month from 1961-1990 (Marion and Wilcox, 1992).

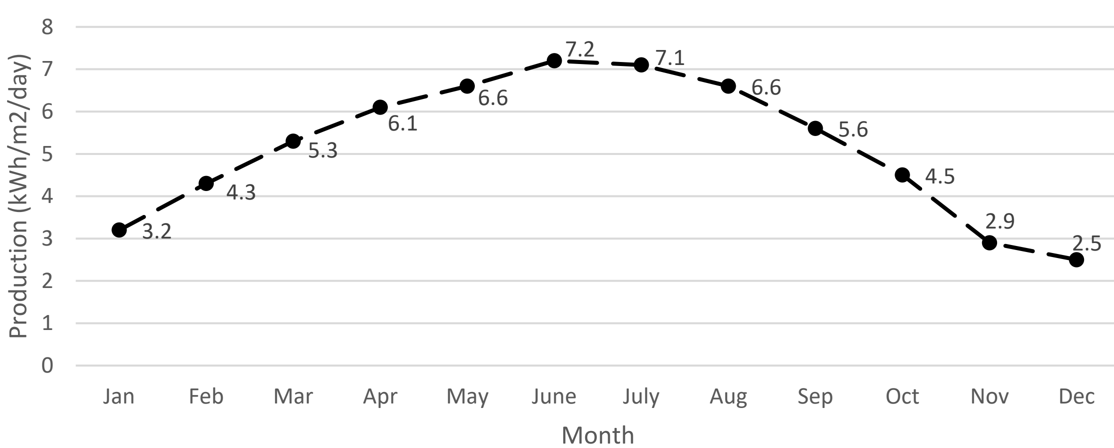

Figure 3: Average daily solar energy production in Williamsport, PA, 1961-1990 (Marion and Wilcox, 1992).

Calculation 2.1 shows the result for the solar panels from Equation 2.1, giving a theoretical annual yield of 2660 kWh.

$$E\left(\frac{kWh}{yr}\right) = 1.75\ (kW) * \frac{5.2\left(\frac{kWh}{m^2 * day}\right)}{1\frac{kW}{m^2}} * 365\left(\frac{days}{yr}\right) * 0.80 = 2660\frac{kWh}{yr} \qquad \text{(C2.1)}$$

Despite the theoretical numbers, actual yield varies at the Eco-Machine™. In November 2019, the inverter read that the solar panels' lifetime generation was approximately 21,400 kWh. The panels began operation in November of 2006, with an average annual production of 1,640 kWh/yr, if it is assumed the solar inverter was never reset. If the inverter was reset, it was most likely in August 2011 after the facility was retrofitted for research and restarted. In this case, average annual production would increase to about 1,900 kWh/yr, which is closer to the anticipated theoretical yield of the solar panels (2,660 kWh/yr).

Between November 2018 and November 2019, a total of 2,191 kWh of energy was produced in 364 days. This is higher than the annual average of 1,640 kWh/yr; however, the measured production is still approximately 83% of the theoretical yield of 2,660 kWh/yr, which is equivalent to a 17% loss. In general, solar panels are expected to lose approximately 1% of productivity each year (Sarai, 2017). In one study, it was found that dirty solar panels lose an average of 3.5% annual yield compared to clean panels (HE Solar, 2017). Given there has been no documented cleaning since installation, a 17.5% decrease (14% from 14 years of life, 3.5% from assumed minimal maintenance) from theoretical production is a reasonable theoretical estimate of energy loss over time compared to the actual 17% loss. Approximately 2,200 kWh of energy was produced in one year of operation between 2018-2019, so this current data will be used as the value for annual energy production by solar panels.

In this study, data was collected from the solar inverter readout from September 2018 to December 2018, and again from August 2019 through February 2020. Figure 4 shows interpolated data of the average monthly energy production from 2019-2020. Since the data collected was not always on the first day of each month, interpolation was necessary. The process for interpolation can be found in Appendix C. Monitoring was not conducted continuously every month, so there is a gap during the spring and summer, but the data collected follows closely to the pattern seen in the theoretical values of Figure 3. In several of the months documented, energy production was higher than the theoretical value. This indicates that the solar panels were operating properly during the course of this study.

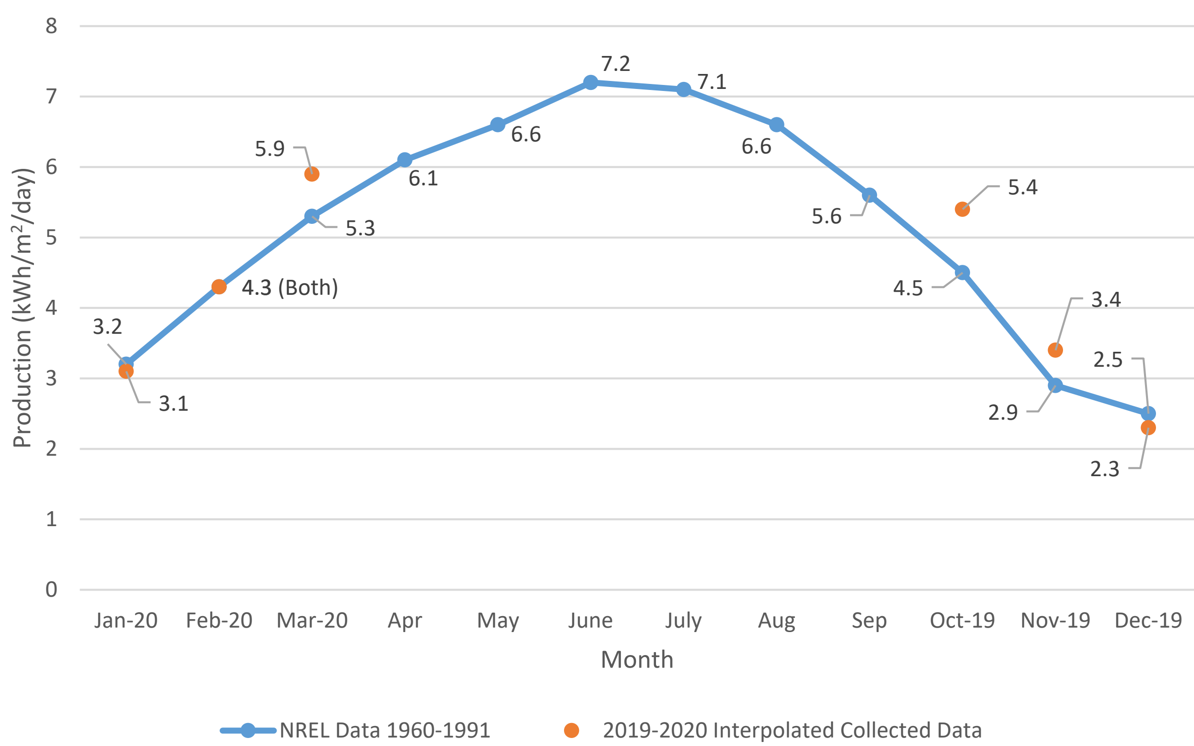

Figure 4: Monthly solar energy production at the Eco-Machine™, 2019-2020, overlain on typical NREL data for Williamsport, PA (Marion and Wilcox, 1992).

2.1.2 Duckweed Energy Production

Since duckweed is a floating aquatic plant, maximization of duckweed growth is dependent on the available surface area of water. In the Penn State Eco-Machine™, duckweed grows in OA3, the clarifier, and the pond, each with diameters of 67.5", 52", and 60", respectively. This results in surface areas of 2.56 m^2, 1.37 m^2, and 1.82 m^2. The clarifier has a section of the surface blocked by a baffle to prevent short circuiting in the clarifier, leaving approximately 71% of the surface available for duckweed, which decreases surface area to 0.97 m^2. A diagram of the clarifier's available surface area for duckweed growth can be seen in Figure 5. Assuming duckweed completely covers the surface of the OA3 and the pond, there is a total of 5.35 m^2 of surface area for duckweed to grow in the system. Duckweed will grow at a rate of 50 g/m^2-day under optimal conditions, or 30 g/m^2-day under typical controlled conditions (Leng et al., 1995).

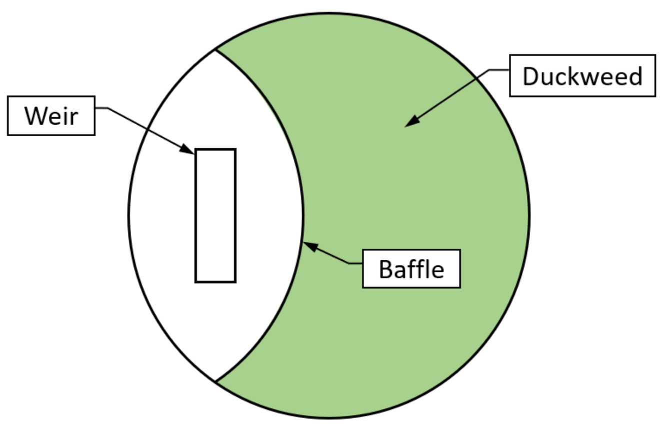

Figure 5: Clarifier plan-view schematic (not to scale).

At the Eco-Machine™, duckweed growth rates in water taken from OA3 have been measured. During continuous-flow tray tests run from January 2017-May 2017, the maximum growth rate for duckweed in OA3 water was 10.1 g DW/m^2-day, with an average value of 6.7 ±

2.3 g/m^2-day (Roman and Brennan, 2019). The maximum duckweed growth rate was 14.0 g/m^2-day for duckweed grown in wastewater from OA1 in April 2017 (Roman, 2019). Duckweed can theoretically reach growth rates of 50 g/m^2-day or more during the summer months, so the maximum value of 14.0 g/m^2-day from OA1 will be used as a conservative annual average for duckweed found in the Eco-Machine™. Although it is the maximum value from the study, it is for the coldest times of the year. This growth rate is not from OA3, but it is more representative of an annual average since duckweed production increases substantially during the summer.

In a previous study, duckweed harvested from OA3 was found capable of producing 10.3 ± 0.0 kJ/g of duckweed by coupling the production of bioethanol and biomethane. This was done by placing the fermented duckweed in an anaerobic digester to produce methane (Calicioglu and Brennan, 2018). Using these conversions, annual energy production from duckweed grown in the three tanks (OA3, clarifier, pond) is anticipated to be as high as 33.8 kWh/yr, 12.0 kWh/yr, and 26.6 kWh/yr, respectively. This yields a total theoretical energy production from duckweed as 78.2 kWh/yr, in the current configuration. Calculation 2.2 shows the result of theoretical bioenergy production from duckweed grown in all three tanks. Supporting calculations can be found in Appendix C.

$$5.35\ m^2 * \frac{14.0\ g}{m^2 * day} * \frac{10.3\ kJ}{g} * \frac{1\ kWh}{3.6 * 10^3 kJ} * \frac{365\ days}{1\ yr} = 78.2 \frac{kWh}{yr} \qquad \text{(C2.2)}$$

2.2 Energy Consumption

The Penn State Eco-Machine™ has multiple components which require energy for proper operation. There are pumps throughout the facility to recycle wastewater through the system to ensure effective treatment. Compressors provide an oxygen-rich environment in two of the three aerobic tanks, and a humidifier simulates a tropical environment during dry times of the year. A furnace is required during winter months to keep the greenhouse at 65°F or above, allowing for treatment by tropical vegetation year-round. In order to utilize duckweed for biofuel production, it must be dried first, which also requires energy.

2.2.1 Mechanical Devices

The humidifier uses electricity during the hot and dry season of summer, most notably July and August. The Honeywell 365A powered flow-through humidifier is rated at 0.7 A and 120 V, giving a wattage of 84 W (P=IV). According to the manufacturer, the humidifier can operate at up to 99% efficiency. With an assumption that it runs for 8 hours per day through the months of July and August, the humidifier uses 41 kWh/yr as shown in Calculation 2.3:

$$\frac{84\,J}{s} * \frac{3600\,s}{1\,hr} * \frac{8\,hr}{1\,day} * \frac{60\,days}{1\,yr} * \frac{1\,kWh}{3.6 * 10^6 J} = 41\frac{kWh}{yr} \qquad \text{(C2.3)}$$

Energy consumption by the humidifier is difficult to estimate due to the need for constant monitoring. However, since it is a small amount compared to other aspects of the system, it should not affect the total energy consumption by a considerable amount.

2.2.2 Pumps and Compressors

There are three hydraulic pumps in the system that use energy. Every pump has a power rating and an efficiency, and these can be used to determine annual energy production, as shown in Equation 2.4:

$$Power\ (kW) * \frac{Usage\ (\text{min})}{1\,day} * \frac{1\,hr}{60\,min} * \frac{365\,days}{1\,yr} = Power\left(\frac{kWh}{yr}\right) \qquad \text{(E2.4)}$$

The influent pump, located in the holding tank, pumps wastewater into CA1. It is a Utilitech Pro ½ HP Sewage Pump (Model #58112-UTL1) that is capable of pumping 128 GPM. This horsepower is equivalent to 0.37 kW (1 hp = 0.7457 kW). This pump runs for approximately one minute every 90 minutes, equaling 16 minutes per day. The energy used per year is equal to 36 kWh when these values are substituted into Equation 2.4 (see Calculation 2.4):

$$0.37\ kW * \frac{16\ min}{1\ day} * \frac{1\ hr}{60\ min} * \frac{365\ days}{1\ yr} = 36\frac{kWh}{yr} \qquad (C2.4)$$

Each mechanical device is rated with an efficiency due to energy loss during conversion from one energy form to another. The influent pump's efficiency is 75%, so 27 kWh of the 36 kWh generated annually is used for pumping, with the remaining 9 kWh lost.

The internal recycle pump is a Utilitech pump rated at 1 hp (Model #58410-UTL1) and runs for one minute 16 times per day at 75% efficiency. Using these numbers and the same unit conversions, the internal recycle pump uses 73 kWh/yr and releases 18 kWh/yr as waste. Two Sweetwater Rotary Vane Air Compressors rated at 0.75 hp (0.56 kWh) are used to aerate the open aerobic tanks and run for a total of 8 hours per day, resulting in an energy consumption of 1635 kWh/yr. Given an average of 81% efficiency, 311 kWh/yr is wasted energy. The external recycle pump is rated at 0.5 hp, and only runs once for one minute every three hours, resulting in a consumption of 18 kWh/yr. At 75% efficiency, 5 kWh/yr is lost to energy transfer. This yields a total of 1761 kWh in annual consumption by pumps, and an energy waste of 343 kWh/yr. Pump and compressor calculations can be found in Appendix C.

The air compressors are running at 8 hrs/day to keep dissolved oxygen concentrations above 2 mg/L as the microbial communities break down the high solids that are currently flowing through the system. This is an usually high operation time, as they normally aerate for 6 hrs/day. If usage was changed to the lower time, energy consumption would reduce to 1226 kWh/yr, which is a 25% decrease. However, 8 hrs/day will be used in this study because this is the current setting.

2.2.3 Duckweed Energy Consumption

To use duckweed for biofuel, the moisture content must be lowered from 92%, its approximate natural state, to a maximum of 20% (Milledge and Heaven, 2014). Duckweed requires heating to 60°C for 12 hours for the moisture content to reach 20%. Using a 92% moisture content, 26.9 g/m^2-day of naturally moist duckweed can be converted into 14.0 g/m^2-day of dry duckweed. The energy required to dry duckweed is $4.346 * 10^{-5}$ kWh/g of moist duckweed (Calicioglu, 2019). Given a total surface area available for growing duckweed in the Eco-Machine™ as 5.35 m^2, Calculation 2.6 shows the total energy consumption of the duckweed drying process.

$$5.35\ m^2 * \frac{\frac{26.9\ g}{m^2}}{day} * \frac{4.346 * 10^{-5}\ kWh}{1\ g} * \frac{365\ days}{1\ yr} = 2.3 \frac{kWh}{yr} \quad \text{(C2.6)}$$

Drying duckweed consumes little energy compared to what it produces (-2.3 vs. 78.2 kWh/yr), meaning duckweed has the potential to be net-energy positive by 75.9 kWh/year at full capacity. Table 1 below provides a summary of the energy balance considering everything except propane.

Table 1: Solar and duckweed energy production vs. energy consumption (excluding propane) in the Penn State Eco-Machine™.

Component	Energy Production (kWh/yr)	Energy Consumption (kWh/yr)
Solar Panels	2200.0	
Duckweed	78.2	-2.3
Humidifier		-41.0
External recycle pump		-18.0
External pump		-36.0
Internal recycle pump		-73.0
Air compressor		-1761.0
Σ	2278.2	-1931.3
Net Energy	+347 kWh/yr (produced)	

2.2.4 Propane

The Eco-Machine™ has two 120-gallon propane tanks located to the side of the building that are refilled biweekly during wintertime by Amerigas Inc. During the winter, the greenhouse is kept at a minimum of 65ºF. According to propane usage data from 2018-2020, this takes an average of 1,077 ± 80 gallons per year (Amerigas Inc., 2020). However, extrapolation was necessary to estimate propane consumption for the remainder of the 2019-20 winter. These calculations can be seen in Appendix C. Gas furnaces can operate anywhere between 78% and 96.6% efficiency according to U.S. Government testing of furnaces that are similar to the one installed at the Eco-Machine™. The Eco-Machine's™ furnace is Energy Star™ rated at 92.2% efficiency, which is above average. One gallon of propane produces 91,600 Btu of heat energy, and there are 3,412 Btu in 1 kWh. Calculation 2.5 shows the average amount of energy that is used by propane.

$$\frac{1077\ gal}{1\ yr} * \frac{91{,}600\ Btu}{1\ gal} * \frac{1\ kWh}{3412\ Btu} = 28{,}900\ \frac{kWh}{yr} \qquad \text{(C2.5)}$$

This amount of energy consumed exceeds the energy produced by the solar panels (2200 kWh/yr) and duckweed at its potential capacity without a vertical farming system (78.2 kWh/yr). Energy waste accounts for 2250 kWh/yr from propane alone, which is more than the energy waste from the combined electrical components. In total, energy waste is approximately 2,583 kWh/yr from all mechanical components and propane, as seen in Table 2. Heating the Eco-Machine™ to maintain temperatures throughout the winter in central PA makes the energy consumption of the system surpass the energy production of the solar panels, as seen in Table 3.

Table 2: Energy waste in the Eco-Machine™ due to equipment inefficiencies.

Component	Energy Waste (kWh/yr)
Humidifier	~0
External recycle pump	5
External pump	9
Internal recycle pump	18
Air compressor	311
Propane	2,250
Σ	2,593

Table 3: Solar and duckweed energy production vs. total energy consumption in the Penn State Eco-Machine™.

Component	Energy Production (kWh/yr)	Energy Consumption (kWh/yr)
Solar Panels	2200.0	
Duckweed	78.2	-2.3
Humidifier		-41.0
External recycle pump		-18.0
External pump		-36.0
Internal recycle pump		-73.0
Air compressor		-1761.0
Propane		-28900.0
Σ	2278.2	-30831.3
Net Energy	-28,533 kWh/yr (consumed)	

The air compressors are responsible for approximately 91% of the energy consumed by all mechanical devices. After including the propane energy expenditure, this percentage decreases to about 5.5%, with propane now contributing approximately 94% of total energy consumption by the Eco-Machine™. Most conventional WWTPs do not heat an entire treatment facility during the winter since flora are not a necessity for the operation of a normal facility. Figure 6 depicts a study on US WWTP average energy consumption distribution (Leman, 2017). It can be seen aeration and pumps generally account for approximately two-thirds of all energy consumption at a conventional WWTP, and aeration accounts for about one-half.

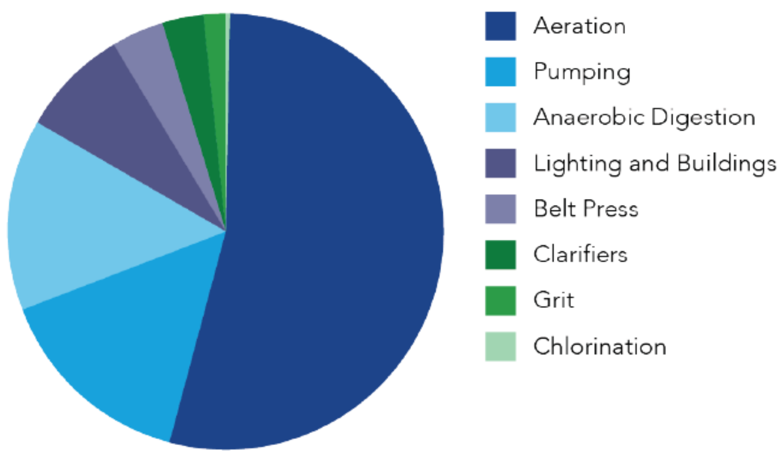

Figure 6: Conventional WWTP energy consumption breakdown (Leman, 2017).

At the Penn State Eco-Machine™, aeration accounts for a much higher proportion (91%) because the depth of the aeration tanks requires a high supplemental oxygen supply through the water. This is not customary of many Eco-Machines™, as many have shallower, wider tanks that require less aeration. Also, wastewater passes through a grit chamber at the PSU WWTP before arriving, which eliminates initial treatment energy needs at the Eco-Machine™.

2.2.5 Other Energy-Consuming Components

The Eco-Machine™ has several instruments that use energy which have been neglected in this analysis. The windows use electricity to open and close, but the amount of energy used is not enough for consideration. The lights are seldom used, so the energy consumption of the lights was also neglected.

2.3 Energy Comparison to Conventional WWTPs

Due to the energy consumed for heating the greenhouse in the winter, the Eco-Machine™ is currently net-energy negative. This is not an unexpected result, as the EPA recognizes that Eco-Machines™ consume energy to operate when greenhouses are necessary (EPA, 2002). Without a greenhouse, construction and operating costs for Eco-Machines™ decrease significantly, further supporting the use of larger-scale Eco-Machines™ in the southern USA and in low-latitude environments (EPA, 2002). Eco-Machines™ are more expensive than conventional WWTPs at larger scales (> 1 million GPD), but they are very cost effective at a smaller community scale (EPA, 2002).

If propane consumption is ignored, the Penn State Eco-Machine™ consumes 1931 kWh/yr, shown in Table 1. At the typical flow rate of 700 GPD, the Penn State Eco-Machine™ consumes 2.0 kWh/m^2_{ww}, as seen in Calculation 2.6.

$$\frac{1931\ kWh}{yr} * \frac{1\ yr}{365\ days} * \frac{1}{700\ GPD} * \frac{1\ gal}{3.785\ L} * \frac{1000\ L}{1\ m^3} = 2.0\ {}^{kWh}/_{m^3_{ww}} \qquad \text{(C2.6)}$$

At conventional WWTPs, energy consumption ranges from 0.20-1.0 kWh/yr (Maktabifard, 2018), which is lower than the Penn State Eco-Machine's current average. Since the open aerobic tanks are proportionally deeper than most, they require more energy to properly aerate, which is a large reason why the proportion of energy consumed for aeration is higher than many other facilities. If this were a larger scale facility, its energy consumption per volume of treated wastewater should decrease and may approach the range of a conventional system (EPA, 2002).

2.4 Beneficial Uses of Duckweed

Although duckweed conversion into biofuel is highly efficient relative to other common feedstocks, the current low market value of bioethanol reduces economic feasibility to a minimum. Fortunately, other avenues for duckweed utilization are available and can be explored to improve the sustainability of the Eco-Machine™. Instead of harvesting duckweed for bioethanol production, it can be placed in an anaerobic digester, producing methane to heat the facility. This is performed at some conventional WWTPs where the biogas is used for heating, electricity, or sold to local gas companies (Leman, 2017). The productivity of duckweed to produce strictly methane through anaerobic digestion is 6.8 ± 0.0 kJ/g TS, which is approximately two-thirds of the energy production from the coupled process of bioethanol and methane (10.3 ± 0.0 kJ/g TS) (Calicioglu and Brennan, 2018). Quality methane furnaces have efficiencies of 90-98.5% (Maltuka, 2013), so energy waste would not increase. Other Eco-Machines™ that require heating should consider natural gas instead of propane if a fossil fuel energy source is the only available option for heating the greenhouse during winter months.

If methane were produced through anaerobic digestion from duckweed and plant litter at the Eco-Machine™, the facility could be partially heated by its own byproducts. Methane yield from raw duckweed results in 6.8 ± 0.0 kJ/g TS (Calicioglu and Brennan, 2019). Throughout an entire year with an average growth rate of 14.0 g/m^2-day, the Eco-Machine™ can produce 51.6 kWh/yr, as shown in Calculation 2.7:

$$\frac{14.0\ g\ TS}{m^2 * day} * \frac{365\ days}{1\ yr} * \frac{6.8\ kJ}{g\ TS} * \frac{1\ kWh}{3600\ kJ} * \frac{1\ mol\ C_3H_8}{44\ g\ C_3H_8} * 5.35\ m^2 = 51.6\ kWh/yr \qquad (C2.7)$$

It is shown in Calculation 2.5 that the greenhouse needs approximately 28,700 kWh/yr for heating, so duckweed production over an entire year from OA3, the clarifier, and the pond would be able to heat the greenhouse for a few hours on a winter night. Even though burning methane would negatively affect the direct carbon balance computations, the overall sustainability may improve because less propane would be required. If a life cycle assessment was performed, it would likely show that producing methane on site is more productive and cost effective than transporting and burning propane.

With current duckweed production in the system, it theoretically could only contribute 2% of the total energy production. Considering the cost of drying the duckweed, the net profit of producing duckweed for biofuel in the Eco-Machine™ is not currently at a scale that can be effective. The price of fossil fuels in today's market decreases the feasibility of duckweed-based biofuels (Calicioglu, 2019). However, harvesting duckweed for agriculture has strong potential given its variable uses. It can be added to fertilizer and used as a feed for livestock, making it a valuable resource with potential to make an impact in the agricultural industry in the future. Currently, research is being conducted at Penn State to determine duckweed's ability to be used as a protein supplement for agricultural fodder (Roman & Brennan, 2019). The current market value of protein is the most economic path to justify expanding duckweed growth in the system (Calicioglu, 2019). If it proves to be an effective protein supplement, duckweed could have a positive impact on the agricultural industry.

2.5 Recommendations and Future Work

While observing the solar panels, it was noted that the expansion fluid located on the sides of the solar tracker, designed to adjust the direction that the panels point, was not performing accurately. The panels were either not adjusting to point at the sun at the optimum angle or took a long time to stabilize at the ideal angle. An inspection should be done to ensure that the panels are operating properly. Also, the Eco-Machine™ greenhouse has not been inspected for air leaks. Ensuring the Eco-Machine™ is sealed properly can reduce propane consumption during the winter, which in turn would decrease carbon emissions, energy consumption, and operating costs.

Automatic dissolved oxygen (DO) monitoring and a feedback control system could reduce energy consumption of the air compressors, which are responsible for a majority of electrical energy consumption in the Penn State Eco-Machine™. The control system could be programmed to turn the air compressors on only when DO concentrations drop below a set point (ex., 2 mg/L). This could reduce electrical energy consumption considerably, and installing the controller could have a desirable return on investment.

2.6 Conclusion

Due to the relative size of the Eco-Machine™, its energy efficiency is lower than most conventional WWTPs. However, its electricity needs are powered completely by a 1.75 kW solar array with a solar tracker. Propane usage for heating causes the facility to be net-energy negative, but the Eco-Machine™ would be net-energy positive in warm climate regions where heating is unnecessary. Though duckweed has potential as an energy source through fermentation and anaerobic digestion, its future as an agricultural resource appears to have more potential to positively impact the bioeconomy.

3.0 Carbon Mass Balance

3.1 Background

Similar to the energy balance, the system's ability to remove and store carbon during wastewater treatment is an important aspect of the Eco-Machine's™ purpose. Previous studies have found that wastewater treatment has a significant impact on global greenhouse gas emissions, and it is imperative to analyze alternative methods that can both continue to treat wastewater to acceptable standards and minimize environmental impacts.

Wastewater from the primary clarifier of the Penn State WWTP is delivered to the Eco-Machine™ to avoid a harmful accumulation of grit and oils in the Eco-Machine™ system. This results in a removal of approximately 30% of carbonaceous biological oxygen demand (CBOD) from the raw wastewater (Sheehan, 2012).

The carbon mass balance during two different time periods will be analyzed and compared in this study. There are several reasons why a carbon balance will be done for each time period. Data on chemical oxygen demand (COD) was taken during the latter half of 2016, and then again during the latter half of 2019 and continued into 2020. In 2016, the flow rate was at 700 GPD; however, the flow rate was decreased to 400 GPD in 2019 because a new external pump was installed that grinds solids and forces them through the system, which in turn requires a higher HRT (i.e., lower flow rate) for thorough treatment.

Wastewater arriving by truck at the Eco-Machine™ each week was measured for COD during refilling of the holding tank. During 2016, COD measurements were taken from wastewater as it came out of the delivery truck and from wastewater as it exited the influent pipe before reaching CA1. Even though wastewater exiting the influent pipe is a better representation of influent COD to the Eco-Machine™, it was only sampled in the 2016 data set. In addition, the COD standard deviation was almost twice as high for samples taken from the influent pipe than for those taken from the truck. For these reasons, the truck COD will be considered as the influent COD for the facility in both time periods. The average COD for wastewater arriving at the Eco-Machine™ was 238.6 ± 36.1 mg/L in 2016 and was 332.0 ± 159.6 mg/L in 2019-20, as shown in Figure 7. The effluent can be considered the pond's average COD concentration of 14.4 ± 3.2 mg/L in 2016 and 25.2 ± 10.0 mg/L in 2019-20.

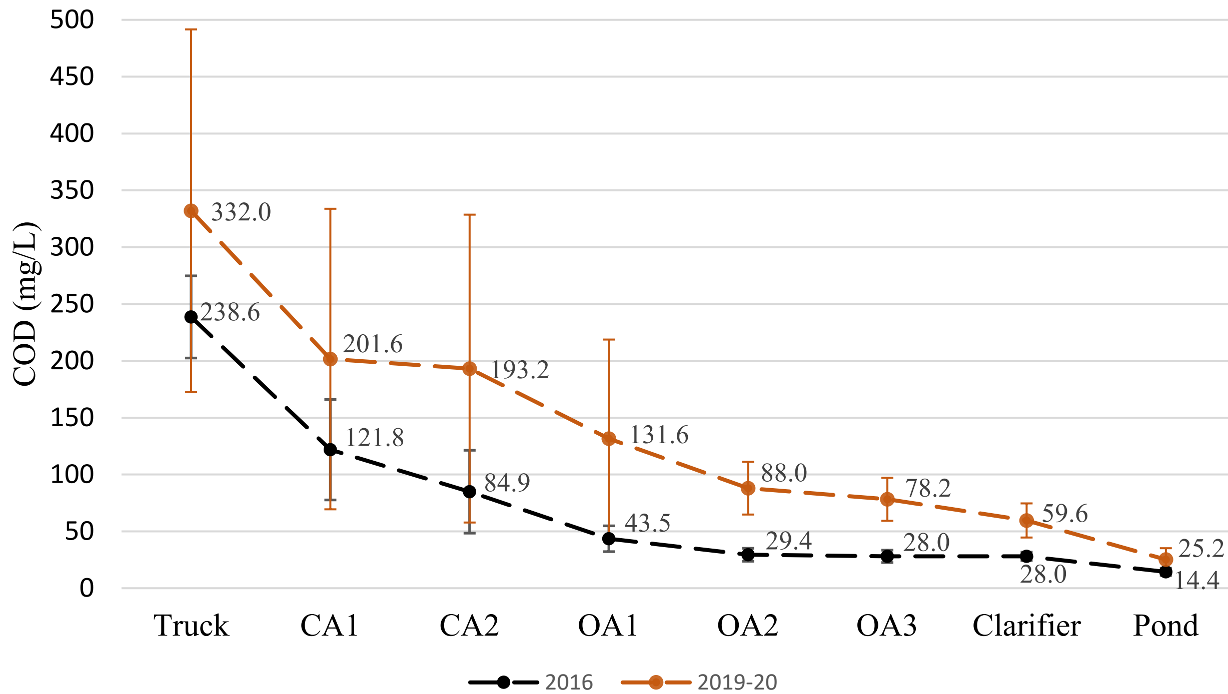

Figure 7: Average COD profile throughout the Eco-Machine™ (2016 and 2019-20). Error bars represent one standard deviation of average values.

In order to convert COD into a carbon flow rate, a few values must be assumed. The chemical composition of domestic wastewater can be approximated using the chemical formula $C_{10}H_{19}O_3N$ and can be estimated to decompose through the following series of reactions:

$$2C_{10}H_{19}O_3N + 25O_2 \rightarrow 20CO_2 + 16H_2O + 2NH_3$$

$$NH_3 + 2O_2 \rightarrow NO_3^- + H^+ + H_2O \qquad \text{(E3.1)}$$

To respond to maintenance concerns and help optimize performance, the flow rates of the internal and external recycle lines were variable during each time period; unfortunately, as the timing of the changing flow rates was not noted during this study, the influence of both recycle lines will be neglected here due to uncertainty. This study occurred during a portion of the COVID-19 pandemic, which limited access to the Eco-Machine™ log book where this data is stored. Assuming flow rates for the recycle lines could lead to misleading assumptions and unrealistic results. With a COD entering the Eco-Machine™ at 238.6 mg/L in 2016, the carbon influent per day can be calculated to be 94.8 g C/day. The conversion for carbon influent is shown below in Calculation 3.2.

$$\frac{238.6\, mg\, COD}{L} * \frac{1\, mg\, O_2}{1\, mg\, COD} * \frac{1\, mmol\, O_2}{32\, mg\, O_2} * \frac{2\, mmol\, WW}{25\, mmol\, O_2} * \frac{10\, mmol\, C}{1\, mmol\, WW} * \frac{12\, mg\, C}{1\, mmol\, C}$$

$$* \frac{3.785\, L}{1\, gal} * \frac{700\, gal}{1\, day} * \frac{1\, g}{1000\, mg} = 189.7\, g\frac{C}{day} \qquad \text{(C3.2)}$$

The same calculation can be done for the 2019-20 values. Given a COD influent of 332.0 mg/L, this equates to 105.8 g C/day with a flow rate of 400 GPD. The carbon flow rate decreases proportionally to the COD concentration as seen in Figure 8. As COD is removed, less carbon flows through each tank.

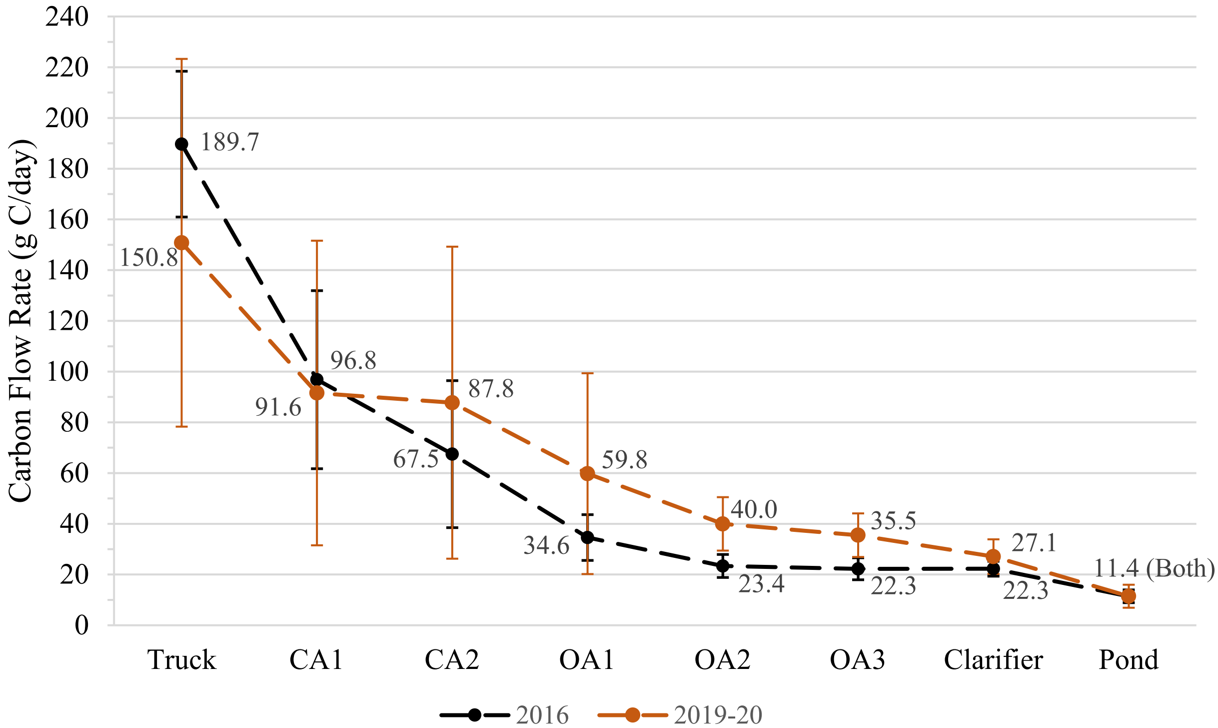

Figure 8: Average carbon flow profile in the Penn State Eco-Machine™ (2016 and 2019-20). Error bars represent one standard deviation of average values.

3.2 Results and Discussion

3.2.1 Closed Anaerobic and Anoxic Tanks

The first closed anaerobic tank (CA1) receives influent directly from the holding tank. This influent is not all directly from the PSU WWTP since about 50% of wastewater from the clarifier is recycled back into the holding tank. According to the carbon flow profile in Figure 8, approximately half of influent COD is removed in CA1 by anaerobic microorganisms. Due to the lack of oxygen, microbial growth is slow compared to aerobic conditions. Biosynthesis likely accounts for approximately 20% of the carbon consumption by anaerobes in the tank, and the remaining 80% of COD is assumed to be used for cellular respiration and released as carbon dioxide (R. Brennan, personal communication, January 2020). The ratio of COD to CBOD must be known to determine exactly how much COD is able to be oxidized by microorganisms. In general, domestic wastewater that has passed through the primary clarifier has a COD/CBOD ratio ranging from 1.6-2.5 (University of Hamburg, 2013). The COD/CBOD ratio will be taken as 2.0 for the average of the range. This ratio will reduce the available COD to half of the total carbon flow, as seen in Calculation 3.3.

$$\frac{92.9\ g\ C}{day} * \frac{1.0\ g\ biological\ carbon\ (CBOD)}{2.0\ g\ total\ carbon\ (COD)} = 46.4\ g\ C/day \qquad \text{(C3.3)}$$

Similar to CA1, microorganisms in CA2 continue to break down wastewater in conditions where pure oxygen is not present. However, oxygen in the form of nitrate exists due to the internal recycle line from OA3, which in effect increases the amount of energy available to microorganisms. Though there is a difference in microbial growth rates, this difference will be neglected to be conservative. The same ratio can be taken for carbon's contributions to respiration and biosynthesis in CA2.

The fraction of COD that it not amenable to biological degradation (i.e., the recalcitrant COD), typically settles in tanks and is removed as sludge at conventional WWTPs. Recalcitrant COD removal has the highest efficiencies within the municipal wastewater industry compared to other industries, such as industrial, agricultural, and landfill leachate wastewaters, due to less complex compositional compounds in domestic wastewater (Vymazal, 2008). There are many uncertainties, however, in the Eco-Machine™ due to the lack of monitoring of non-biological COD pathways. It can be hypothesized the recalcitrant COD is either consumed by macroinvertebrates, settles in tanks, or attaches to available surfaces such as plant roots or rocks (i.e., accretion). Most of the recalcitrant COD consumed is most likely stored in biomass.

However, assigning a numerical value to recalcitrant COD removal would imply much higher certainty than what is presently available. Since the COD/CBOD ratio was also assumed for this study, it is best not to assume definite recalcitrant carbon pathways. For this reason, recalcitrant carbon flow in all tanks will be represented over the full possible range from 0% to 100% storage or release of carbon dioxide. Table 4 summarizes the path for carbon extracted from wastewater in CA1 and CA2, where the biological carbon flow includes a COD/CBOD ratio of 2.

Table 4: Carbon path in CA1 and CA2.

	2016 Data		**2019-20 Data**	
	CA1	**CA2**	**CA1**	**CA2**
Biosynthesis:Respiration Ratio	20:80	20:80	20:80	20:80
Carbon Flow Loss (g C/day)	92.9 ± 45.3	29.3 ± 45.5	59.2 ± 94.0	3.8 ± 85.9
Biological Carbon Flow Loss (g C/day)	46.4 ± 22.7	14.7 ± 22.8	29.6 ± 47.0	1.9 ± 43.0
Carbon Storage (Biosynthesis) (g C/day)	9.3 ± 4.5	2.9 ± 9.1	5.9 ± 9.4	0.4 ± 8.6
Biological Carbon Release (Respiration) (g C/day)	37.1 ± 18.2	11.7 ± 36.4	23.7 ± 37.6	1.5 ± 34.4
Non-Biological (Recalcitrant) Carbon (g C/day)*	± 46.4 (stored or released)_	± 14.7 (stored or released)_	± 29.6 (stored or released)_	± 3.8 (stored or released)_

*Recalcitrant carbon flow will be considered a range, either storage or released as carbon dioxide.

There is a smaller decrease of carbon flow in CA2 because CA1 already removed much of the carbon from the wastewater. In CA2, there is a large difference in carbon flow removal between 2016 and 2019-20 data. This may be due to a slower flow rate, resulting in a majority of anaerobic degradation capacity occurring in CA1, with CA2 unable to oxidize a large amount.

3.2.2 Open Aerobic Tanks

3.2.2.1 OA1 and OA2

OA1 is the first location that wastewater is exposed to an oxygen-rich environment. Aerobic microorganisms continue to break down carbon compounds, which are then utilized in the tanks and in processes later in the system. Unlike anaerobes, aerobes have a higher growth rate (and therefore higher carbon storage capacity) compared to anaerobes. Contrary to anaerobes, this study will assume that approximately 80% of carbon removed is stored via biosynthesis, while 20% is used for respiration. Due to the existence of taro plants (Figure A7) in OA1 and OA2, a separate study would have to be conducted to determine an accurate representation of carbon uptake, but this study will consider the growth of taro a separate entity from COD removal. Taro plants (Figure A7) undergo the harshest conditions of all the macrophytes since it resides in the first aerobic environments of the wastewater treatment system. The diameters of the floating islands are 48" each, resulting in a total planted surface area of 2.33 m^2 for taro growth.

The adult taro has a high growth rate due to its thick stems and large leaves. In one study the net photosynthesis rate was found to be 10.4 ± 5.2 g C/m^2-day (Saunders et. al, 2012). Since the taro grows in a contained area, the surface area for which is grows can be assumed to be constant at 2.33 m^2. With this photosynthesis rate and surface cover, carbon growth rate can be considered 24.2 ± 12.1 g C/day, as seen below in Calculation 3.4. This is a large range, but growth varies substantially in general.

$$\frac{10.4\ g\ C}{m^2 * day} * \frac{2.33\ m^2}{1} = \ 24.2 \ {}^{g\ C}/_{day} \qquad \text{(C3.4)}$$

Table 5 shows the results for the carbon path in OA1 and OA2. The total range of recalcitrant COD for each tank for both time periods can be found in Table 6.

Table 5: Carbon path in OA1 and OA2 by microorganisms.

	2016 Data		2019-20 Data	
	OA1	OA2	OA1	OA2
Biosynthesis:Respiration Ratio	80:20	80:20	80:20	80:20
Carbon Flow Loss (g C/day)	32.9 ± 30.4	11.2 ± 10.2	28.0 ± 73.2	19.8 ± 41.0
Biological Carbon Flow Loss (g C/day)	16.4 ± 15.2	5.6 ± 5.1	14.0 ± 36.6	9.9 ± 20.5
Carbon Storage (Biosynthesis) (g C/day)	13.1 ± 12.2	4.5 ± 4.1	11.2 ± 29.3	7.9 ± 16.4
Biological Carbon Release (Respiration) (g C/day)	3.3 ± 3.0	1.1 ± 1.0	2.8 ± 7.3	2.0 ± 4.1
Non-Biological (Recalcitrant) Carbon (g C/day)*	± 16.4 (stored or released)	± 5.6 (stored or released)	± 14.0 (stored or released)	± 9.9 (stored or released)

*Recalcitrant carbon flow will be considered a range, either storage or released as carbon dioxide. This is reflected in the carbon balance summary.

Table 6: Recalcitrant carbon flow summary assuming a COD/CBOD ratio = 2. Recalcitrant COD is presented as a range of possible stored or released carbon. All values are in g C/day.

	2016 Data	2019-20 Data
CA1	46.4	29.6
CA2	14.7	1.9
OA1	16.4	14.0
OA2	5.6	9.9
Total (g C/day	± 83.1	± 55.4

Taro 3.2.2.2 OA3: Duckweed

Duckweed growth rates in OA3 were obtained from January through May 2017. At that time, duckweed was on a 5-day harvesting cycle, and the growth rates varied from 1.6 g DW/m^2-day in January to 10.1 g DW/m^2-day in April (Roman, 2019). Since data was taken during times of low growth rates, the highest measured growth of 14.0 g DW/m^2-day will be used as the average growth rate, similar to the energy balance in Section 2.1.2.

A carbon content was obtained for duckweed that grows on a pond at the Living Filter, which receives treated wastewater from the Penn State WWTP that is sprayed onto Pennsylvania State Game Land no. 176. The percent carbon of duckweed found in a pond at this location was

39.1% (Kreider et al., 2019). Although this is not duckweed directly from the Eco-Machine™, it grows in similar environments and can be taken as a representative measurement of carbon content for duckweed at the Eco-Machine™.

As an aquatic plant, duckweed prefers to take up aqueous carbon dioxide versus gaseous CO_2 for photosynthesis. One study completed in Detroit, Michigan, found that duckweed takes 86% of its carbon dioxide from water in a local, hard-water dimictic lake (Filbin and Hough, 1985). Even though this study was not done in wastewater, it will be taken as an approximation for our purposes. Calculation 3.3 shows the steps that Table 7 outlines in detail. Since the carbon removal by duckweed is higher than the average drop in COD, microbial carbon uptake will be neglected in OA3 for conservative purposes.

Table 7: Duckweed carbon removal in OA3.

	A	**B**	**C**	**D**	**E**	**F**
	Surface area (m^2)	Growth rate* (g DW/m^2/day)	Carbon in Duckweed† (%)	Duckweed carbon growth rate (g C/day) **(A*B*C)/100**	Carbon uptake from WW‡ (%)	Carbon removal rate (g C/day) **(D*E)/100**
OA3	2.31	14.0	39.1	12.6	86	10.9

*Estimated duckweed growth rate based on measurements previously performed in the open aerobic tanks.
†Measured carbon content by Kreider et al. (2019) for duckweed in the Living Filter.
‡Estimated duckweed carbon uptake by Filbin and Hough, 1985.

As can be seen in Table 6, carbon flow removal from wastewater (10.9 g C/day) is lower than the duckweed carbon growth rate (12.6 g C/day). This discrepancy is due to duckweed's ability to take CO_2 from both wastewater and the atmosphere. However, the assumed preference of duckweed to uptake 86% of CO_2 from wastewater has a high uncertainty because the original study was done in freshwater (Filbin and Hough, 1985). If these estimates are assumed to be accurate, duckweed carbon flow removal of 10.9 g C/day surpasses OA3 removal by a substantial amount as seen in Figure 8 (2016 data: 1.1 g C/day; 2019-20 data: 4.5 g C/day).

Given the carbon growth rate of duckweed is much higher than the actual carbon flow removal rate, duckweed must be receiving a higher portion of carbon dioxide from the atmosphere. Due to this high difference from carbon flow averages, all microbial activity will be neglected for conservative purposes. The duckweed carbon growth rate of 12.6 g C/day will be taken for the carbon balance analysis because it also incorporates CO_2 removal from the atmosphere.

3.2.3 Clarifier

One of the primary organisms that uptakes COD from the wastewater in the clarifier is duckweed. The duckweed growth rate in the clarifier has not been measured, so the growth rate from OA3 was used as an approximation. The clarifier is 50 in^2 in diameter, but a section of the tank's surface area is blacked with a baffle to avoid duckweed from clogging the exit weir. Approximately 71% of the surface area of the clarifier is available for duckweed growth (see Figure 5). As a result, the clarifier has 0.95 m^2 of duckweed on the surface. Table 8 summarizes the theoretical removal of carbon in the clarifier by duckweed.

Table 8: Theoretical duckweed carbon removal in the clarifier of the Eco-Machine™.

	A	B	C	D	E	F
	Surface area (m2)	Growth rate* (g DW/m2/day)	Carbon in Duckweed† (%)	Duckweed carbon growth rate (g C/day) (A*B*C)/100	Carbon uptake from WW‡ (%)	Carbon removal rate (g C/day) (D*F)/100
Clarifier	0.95	14.0	39.1	5.2	86	4.5

*Estimated duckweed growth rate based on measurements previously performed in the open aerobic tanks.
†Measured carbon content by Kreider et al. (2019) for duckweed in the Living Filter.
‡Estimated duckweed carbon uptake by Filbin and Hough, 1985.

Similar to OA3, duckweed growth in the clarifier surpasses the carbon flow removal average for 2016, but not 2019-20 as seen in Figure 8 (2016 data: 0.0 g C/day; 2019-20 data: 8.4 g C/day). There is a large discrepancy between each time period, but COD measurements may be inaccurate because samples were not filtered prior to analysis, and the presence of any duckweed particulates may have artificially increased the measured COD. The measured soluble COD (sCOD) was 68.8 ± 7.1% (n = 2) of the total COD in the clarifier. However, sCOD was not measured in OA3, so an adjusted COD excluding particulates from duckweed and other potential organisms cannot be accurately determined. The duckweed carbon growth rate of 5.2 g C/day will be taken for the carbon balance analysis for simplicity. Due to unknown parameters of wastewater COD, microbial activity will also be neglected in the clarifier.

3.2.4 Constructed Wetland

There are numerous types of aquatic and non-aquatic plants present in the Eco-Machine™ which contribute to carbon uptake from the wastewater. Growth rates were obtained from the literature for all three of the dominant wetland plants (canna lily, water canna, and calla lily), where the growth rate is a function of the wetland surface area that each plant covers. Since the Eco-Machine™ has space for plants to expand and retract, this number varies significantly throughout the year. During the summer, the greenhouse flourishes due to high growth rates in optimal conditions, and the plants then diminish in autumn as temperatures decrease. Since this study collected data primarily during autumn and winter months, the growth rates and decay rates were low because there was less plant biomass in the greenhouse. However, the summer net-carbon variance would not change significantly compared to winter because growth and decay rates are interdependent and would offset each other.

Given the surface area available for microbial biofilm in the wetland, microbes undoubtedly also contribute significantly to carbon removal. However, to have a conservative estimate, all microbial carbon uptake will be neglected in the calculations that follow, and it will be assumed that plants perform all carbon removal in the wetland.

3.2.4.1 Calla Lily

Calla lily (Figure A6) has a fast growth rate for its size, but the life of a stem is short, resulting in fast turnover. In a study conducted in Brazil, growth rates for the calla lily were reported as the highest net photosynthesis rate per season (Rodrigues et al., 2014). Each season's maximum photosynthetic photon flux density (PPFD) was also documented. As seen in Table 8, the highest rates of net photosynthesis were associated with medium levels of PPFD. Higher light intensity decreased growth due to overexposure, and lower intensity also decreased growth due to a lack of sunlight (Rodrigues et al., 2014).

Table 9: Calla lily optimum seasonal growth conditions adapted from Rodrigues et al., 2014.

	Optimum PPFD ($\mu mol/m^2$-s)	**Net Photosynthesis Rate ($\mu mol\ O_2/m^2$-day)**
Spring	281	6.34
Summer	243	9.76
Autumn	303	7.57
Winter	285.5	5.30

During the summer months in State College, PPFD reaches far above the optimum PPFD, which is similar to Brazilian conditions. However, the higher precipitation rates in Brazil allow for higher possible growth rates than in Pennsylvania. For the purposes of this study, the net photosynthesis rate for the summer will be neglected. Also, the Brazilian study investigated calla lilies while growing from seedlings in the spring, which does not occur at the Eco-Machine™. This means that the spring photosynthesis value is not representative of Eco-Machine™ conditions and will be neglected as well.

To estimate a reliable value for net photosynthesis, it can be assumed the average annual growth rate is the mean of the autumn and winter rates, which is 6.43 µmol O_2 /m^2-day. To convert from oxygen to carbon dioxide, the chemical equation for photosynthesis will be used as follows in Equation 3.5:

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \tag{E3.5}$$

Calculation 3.6 shows the conversion to applicable units in this study.

$$6.43\ {}^{\mu mol\ O_2}\!/_{m^2 s} * \frac{6\ \mu mol\ CO_2}{6\ \mu mol\ O_2} * \frac{1\ \mu mol\ C}{1\ \mu mol\ CO_2} * \frac{1\ mol\ C}{10^6\ \mu mol\ C} * \frac{12\ g\ C}{1\ mol\ C} * \frac{86{,}400\ s}{1\ day}$$

$$= {}^{6.67\ g\ C}\!/_{m^2 * day} \tag{C3.6}$$

The calla lily currently grows in five small but dense bunches throughout the Eco-Machine™ wetland. The total surface area of these bunches is 0.73 ± 0.06 m^2. With its estimated growth rate of 6.67 g C/m^2-day, this results in a carbon intake of 4.9 ± 0.4 g C/day.

3.2.4.2 Canna Lily

Canna lily (Figure A5) is considered to be an efficient terrestrial plant at removing COD in constructed wetlands (Haritash et al., 2015). It prefers to uptake sugars and carbon from the soil versus other methods of growth. It is quick to spread, making it a good plant to cover an entire wetland. It has the potential to remove considerable amounts of COD at high loading rates. It may be indicated in its darker coloring of leaves and stems, similar to taro, that it is prefers to take up nutrients from wastewater. However, this hypothesis was not verified. In one study, it was found that canna lily was able to remove 18.1 g COD/m^2-day at a loading rate of 18.8 g COD /m^2-day, which is 92% efficiency at high loading rates (Haritash et al., 2015). The canna is a resilient wetland plant that has notably high potential in Eco-Machines™. However, 92%

efficiency would be difficult to achieve at the low wastewater loading rate of the Eco-Machine's™ constructed wetland.

At low COD concentrations similar to the Eco-Machine™, canna's growth rate is 13.2 ± 2.5 g DW/m^2-day (DeBusk et al, 1995). In December 2019, a canna lily sample from the Eco-Machine™ wetland was tested for carbon content by combustion by the Agricultural Analytical Services Lab at Penn State. This is only one sample, but it is still a reliable estimation because carbon content varies minimally between plants of the same species and even between species (Schlesinger, 1991). With a carbon content result of 42.7%, a carbon growth rate of 5.64 ± 1.07 g C/m^2-day was calculated. Due to its ability to spread quickly, its surface area varies more than the other wetland plants. Given its average cover of 0.90 ± 0.33 m^2, this results in a growth rate of 5.6 ± 1.1 g C/day. The calculation can be found in Appendix D.

3.2.4.3 Water Canna

The water canna (Figure A8) resides along the sides of the greenhouse. According to a study performed in Thailand, water canna has a growth rate of 8.49 ± 1.29 g DW/m^2-day (Konnerup et al., 2009). Given a carbon content of 45.7 ± 0.41%, this yields a carbon growth rate of 3.88 ± 0.59 g C/m^2-day (Cui et al., 2016).

The water canna can be found throughout the greenhouse, has been able to expand over time, and was recently stripped from an area adjacent to the pond. Measurements of surface cover were not taken until after its removal from around the pond to keep data consistent. With an average surface cover of 1.08 ± 0.11 m^2, a carbon intake of 4.2 ± 0.8 g C/day was calculated and shown in Appendix D.

3.2.4.4 Pond Duckweed

Duckweed present in the pond can be evaluated similarly to that in OA3 and the clarifier. With an assumed growth rate of 14.0 g DW/m^2-day, a surface area of 1.82 m^2, and a percent carbon of 39.1%, a growth rate of 10.0 g C/day can be estimated as a carbon storage rate. Analyzing duckweed growth throughout the Eco-Machine™ yields a combined carbon uptake rate of 27.8 g C/day (OA3 + Clarifier + Pond = 12.6 + 5.2 + 10.0 g C/day) with an estimated capability of removing 24.0 g C/day from wastewater.

3.2.5 Plant Decay

The Eco-Machine™ is currently trimmed between once per week and once biweekly. The trimmings are stored in a compost pile adjacent to the facility and are left to decay naturally in the compost pile.

From the beginning of November to the end of January, plant litter was gathered from the four different plants that live in the system and weighed. Samples were dried to determine moisture content of leaves on the verge of decay. It was determined that the average moisture content is 86.0 ± 0.9%. Each species' mass was measured individually to determine the percent of each plant existing within the plant litter. Since plant litter carbon content varies by species, a carbon content proportional to plant litter type was determined using available carbon content data, as shown in Table 10. Taro growth was assumed to have a carbon content of 46% of the dry matter (Saunders et al, 2012).

Table 10: Plant litter carbon content (CC) measured for wetland plants in this study.

	Measured Litter (%)	CC* (%)	Calculated C (%)	*CC Reference
Calla lily	28.2	45.7	12.9	(Cui et al., 2016)
Canna lily	25.5	42.7	10.9	From this study
Water canna	15.7	45.7	7.2	(Cui et al., 2016)
Taro	30.6	46	14.1	(Saunders et al., 2012)
Σ			45.0	

Between the months of November and January, an average plant litter rate of 41.1 g DW/day was observed. With a weighted carbon percentage of 45.0%, the carbon plant decay is 18.5 g C/day. Tables 11 and 12 show the results of the carbon balance broken down by components for both 2016 and 2019-20 data sets. Duckweed from OA3, the clarifier, and the pond is combined into one entry. In a warm temperate climate or tropical region where greenhouses and heating are unnecessary, an Eco-Machine™ is a carbon-negative system that can remove nutrients according to US-EPA effluent standards.

Table 11: Eco-Machine™ 2016 biological carbon balance summary. A range of ±83 g C/day is provided to indicate uncertainty due to unknown pathways for recalcitrant COD.

Component	**Carbon Storage (g C/day)**	**Carbon Release (g C/day)**
CA1	-9.3	37.1
CA2	-2.9	11.7
OA1	-13.1	3.3
OA2	-4.5	1.1
Total Duckweed	-27.8	
Water Calla	-4.9	
Canna Lily	-5.6	
Water Canna	-4.2	
Black Magic Taro	-24.2	
Plant Decay		18.5
Effluent		11.4
Σ	-96.5	83.1
Net Carbon	**-13 ± 83 g C/day (storage)**	
Carbon Balance Range	**-96 to +70 g C/day**	

Table 12: Eco-Machine™ 2019-20 biological carbon balance summary. A range of ±55 g C/day is provided to indicate uncertainty due to unknown pathways for recalcitrant COD.

Component	**Carbon Storage (g C/day)**	**Carbon Release (g C/day)**
CA1	-5.9	23.7
CA2	-0.4	1.5
OA1	-11.2	2.8
OA2	-7.9	2.0
Total Duckweed	-27.8	
Water Calla	-4.9	
Canna Lily	-5.6	
Water Canna	-4.2	
Black Magic Taro	-24.2	
Plant Decay		18.5
Effluent		11.4
Σ	-92.0	59.9
Net Carbon	**-32 ± 55 g C/day (storage)**	
Carbon Balance Range	**-87 to +23 g C/day**	

3.2.6 Propane

As the primary source for heating during the winter, propane has a large influence on the ability for the Eco-Machine™ to perform properly for several months out of the year. The propane furnace located in the Eco-Machine™ greenhouse converts propane into heat using combustion, shown in the following equation:

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O \quad \text{(E3.7)}$$

The release of carbon dioxide during combustion contributes to not only the energy consumption, but also the carbon footprint of the Eco-Machine™. Although the amount of propane consumed each winter varies by year, 1077 ± 80 gallons of propane can be assumed as an average consumption rate from the Amerigas invoices (see Appendix C), as discussed in the energy balance. Given a propane density of 493 kg/m^3, the carbon release can be averaged throughout the entire year as shown in Calculation 3.8:

$$\frac{1077\ gal\ C_3H_8}{yr} * \frac{3.785\ L}{1\ gal} * \frac{1\ m^3}{1000\ L} * \frac{493\ kg}{1\ m^3} * \frac{1000\ g\ C_3H_8}{1\ kg\ C_3H_8} * \frac{1\ mol\ C_3H_8}{44\ g\ C_3H_8} * \frac{3\ mol\ CO_2}{1\ mol\ C}$$

$$* \frac{1\ mol\ C}{1\ mol\ CO_2} * \frac{12\ g\ C}{1\ mol\ C} * \frac{1\ yr}{365\ days} = 4612\ g\frac{C}{day} \quad (C3.8)$$

This value is nearly 15 times the amount of aqueous carbon that flows through the Eco-Machine™ every day. Propane use only accounts for a few months annually, and its consumption distributed evenly over the entirety of a year is still enough to make the Eco-Machine™ significantly carbon-positive. Tables 13 and 14 summarize the carbon balance with the inclusion of propane.

Table 13: Eco-Machine™ 2016 total carbon balance summary.

Component	**Carbon Release (g C/day)**
Net Biological	**-13 ± 83**
Propane	+4612
Net Carbon	**+4599 ± 83 g C/day (released)**

Table 14: Eco-Machine™ 2019-20 total carbon balance summary.

Component	**Carbon Release (g C/day)**
Net Biological	**-32 ± 55**
Propane	+4612
Net Carbon	**+4580 ± 55 g C/day (released)**

3.3 Carbon Comparison to Conventional WWTPs

Many studies have been conducted on conventional wastewater treatment facilities to determine the effect they have on greenhouse gas (GHG) emissions. Neglecting methane release and sludge production, the Penn State Eco-Machine™ releases approximately 115 g C/day if considering the 2019-20 data using the critical range (59.9 + 55 g C/day of CO_2 release), which had a higher carbon release per gallon (see Table 12). The Eco-Machine™ releases a minimal amount of methane due to the existence of methanotrophs at the top of the anaerobic tanks, so methane release was neglected for this comparison. Also, sludge accumulation in the system is minimal, which is an important benefit of ecological treatment methods. Any sludge that does accumulate in the clarifier is recycled into the holding tank to be treated through the system again, further reducing sludge production.

Unlike Eco-Machines™, sludge and methane are produced at many conventional WWTP facilities. From COD oxidation alone, facilities can release approximately 0.21 kg $CO_{2\ equivalent}/m^3_{ww}$. If a WWTP burns the methane produced, an additional 0.1 kg $CO_{2\ eq}/m^3_{ww}$ is released (Campos et al., 2016). Another study conducted in southern California provided lower averages of 0.197 kg $CO_{2\ eq}/m^3_{ww}$ and 0.044 kg $CO_{2\ eq}/m^3_{ww}$ from aeration and methane release, respectively, for a total of 0.241 kg $CO_{2\ eq}/m^3_{ww}$ (Tseng et al., 2016). The Eco-Machine™, in comparison, releases only 0.077 kg $CO_{2\ eq}/m^3_{ww}$, as seen in Calculation 3.9:

$$\frac{115\ g\ C}{day} * \frac{1}{400\ GPD} * \frac{1\ gal}{3.785\ L} * \frac{1000\ L}{1\ m^3} * \frac{1\ g\ CO_2}{1\ g\ C} * \frac{1\ kg}{1000\ g} = 0.076\ {kg\ CO_{2\ equiv}}\Big/{m^3_{ww}} \quad (C3.9)$$

The Eco-Machine™ therefore theoretically releases only 25 to 32% of the carbon emissions of a conventional treatment plant in the scenario where all recalcitrant carbon is released, which is unlikely (Campos et al., 2016; Tseng et al., 2016). This numerical comparison is an imprecise approximation due to the many assumptions that exist, but it provides a general understanding that Eco-Machines™ significantly decrease carbon emissions compared to conventional treatment methods, even in a critical estimate.

3.4 Recommendations and Future Work

There is potential for the Eco-Machine™ to improve its net-carbon yield more than numbers indicate and that goes beyond the scope of this study. Since propane usage has the strongest influence on the carbon balance, finding an alternative heat source with less of an impact on climate change would have the largest influence. A life cycle analysis of the propane that is received at the Eco-Machine™ would indicate a larger carbon footprint due to extraction, refinement, and transport. Properly sealing the greenhouse, similar to that proposed in the energy balance, would also improve the net-carbon balance of the Eco-Machine™.

The plant decay estimation assumed that 100% of the plant would decay with no burial. This may not be true because natural burial would most likely occur. Also, plant decay does not occur linearly; it is a naturally exponential decrease that infinitesimally approaches 100% decay (Aerts, 1997). An alternative analysis that takes exponential decay of plant litter into account was considered (see Appendix D). In the future, a beneficial use for plant litter would be to compost it for use on the grounds. There is a significant amount of valuable nutrients currently underutilized, as all plant litter is discarded in a compost bin. Regardless of whether plant litter is composted for agricultural use or fermented for biogas energy, the life cycle analysis of plant litter could improve compared to its current lack of utilization.

Recycle flow rates were neglected due to the uncertainty of flow rates during the study periods. If operation of recycle rates were considered, the carbon balance would most likely change. A future study should take recycle rates into account to further improve the estimates determined in this thesis.

Higher growth rate accuracy could be achieved with C-13 monitoring. The addition of a radioisotope at a WWTP presents many regulatory challenges; however, there are other places at Penn State this study could be conducted to improve the accuracy of the carbon balance. This could be investigated in future studies.

3.5 Conclusion

Given the relative size of the Eco-Machine™, it is an efficient system that can be carbon-negative in warm climates. The system is not an optimum size, so it is unable to reach full net-carbon potential, in regard to biological components. The Eco-Machine™ is about 25% carbon-negative for the biological carbon balance, but higher numbers can be achieved in larger systems. Many adjustments can be made to improve the carbon balance in this system, which provides promise to newly installed Eco-Machines™ with optimized system design and operation.

4.0 Duckweed Vertical Farming System

4.1 Introduction

Research has been conducted on Eco-Machine™ duckweed at Penn State since 2011, with many studies currently in progress. There was a desire to expand duckweed production for research and to increase the overall sustainability of the facility. Due to the limitations of the confined greenhouse space, the most effective option to expand duckweed production was to build vertically. This vertical farming system (VFS) was a small-scale experiment to test the ability of duckweed to grow under artificial lighting in containment systems.

4.2 Materials and Methods

4.2.1 Material Characteristics

To determine the size of the VFS, duckweed growth trays were chosen that complied to project-relevant standards. High density polyethylene (HDPE) was determined to be a polymer with enough durability and strength to contain wastewater in a greenhouse environment. Its low flexibility, high strength, and semi-resistance to UV-exposure were suitable for a vertical farming system. HDPE trays used in past duckweed growth experiments at the Eco-Machine™ were reused in this experiment. The trays have outside dimensions of 48” by 15” with a depth of 7.5”. The inside dimensions are 45-3/8” by 13” by 6-7/8”. This results in a surface area of 589.9 in^2, or 0.3806 m^2. Therefore, a maximum total growth area of 1.52 m^2 was available from all four duckweed trays.

It was imperative that the stand chosen could support the trays’ weight and dimensions. A steel stand was selected from the Penn State Surplus store with four shelves each measuring 57” long and 22” wide, which were adequate to hold the trays. There was approximately 18-19” clearance in between each level. Due to shading of trays on lower shelves, grow lights were used to maintain adequate light intensity. Full spectrum lighting was a necessity to provide UV light to the duckweed; however, full spectrum lighting is offered as either red/blue light or white light. White lighting has both red and blue but also includes green, which is why it appears white to the human eye. It is easier to assess plant health under white light, and the addition of green light can potentially provide better growth, as well. Therefore, full spectrum white grow lights were chosen (Monios-L 60W T5 LED), each measuring 4 feet long, which was the length of the trays selected for the system. The grow lights were arranged to be about 9” from the surface of the water to increase the light intensity at the surface. The light intensity from the grow lights ranged between 93-98 μmol/m^2-s, which was lower than anticipated but high enough to provide sufficient light for duckweed growth. A cross sectional schematic is provided in Figure 9 below.

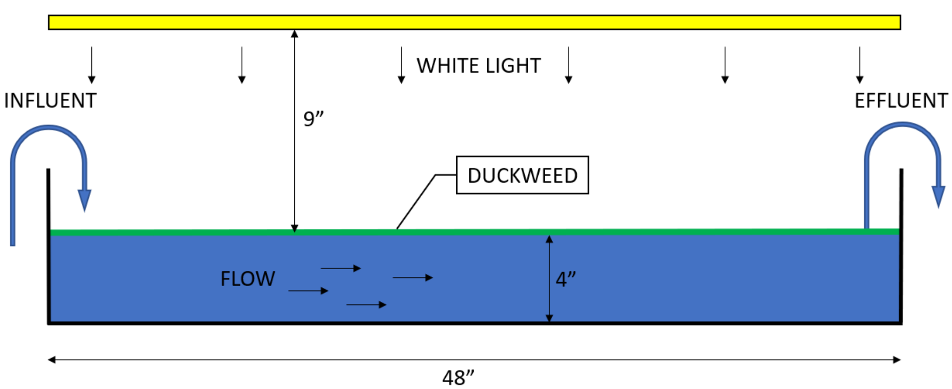

Figure 9: Vertical farming system tray cross section (not to scale).

4.2.4 Assembly and Procedure

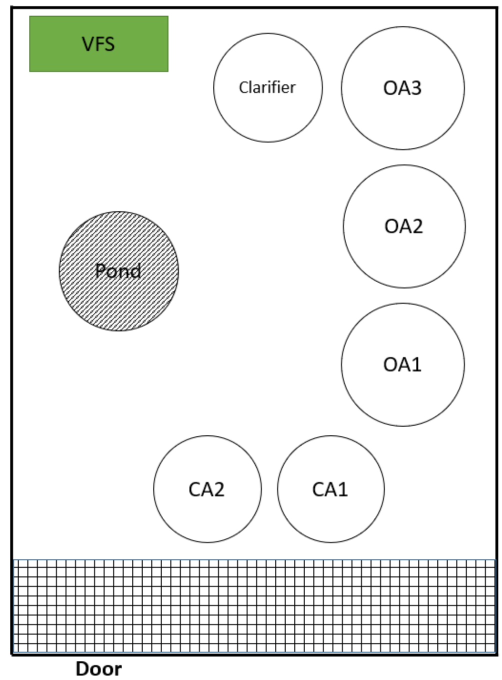

Figure 10: Vertical farming system location (in green).

The vertical farming system was assembled in the far corner of the greenhouse adjacent to the clarifier, shown in Figure 10, for close access to OA3 and the clarifier. The stand was leveled, and tubing was configured so wastewater would flow from one end of the tray to the other, as seen in Figure 9. Peristaltic pumps were used to extract wastewater at approximately 12" below the surface of OA3 to avoid duckweed from entering the tubing and clogging the pump. A hydraulic retention time (HRT) of 24 hours (27 mL/min flow rate) was previously determined to produce adequate growth rates (Brennan and Roman, 2018).

The grow lights were installed for three of the four trays; the tray on the top shelf was exposed to sunlight instead of artificial lighting. To determine the effectiveness of the grow lights, a black cloth covered the bottom and bottom-middle (BM) trays to minimize sunlight exposure. The top-middle (TM) tray was exposed to both a grow light and sunlight, but the sunlight was not as intense as the top tray since it primarily receives indirect sunlight. A photograph of the vertical farming system can be seen in Figure 11.

Figure 11: Photograph of the vertical farming system. A black cloth normally covered the two bottom trays.

A one square-foot frame was used to harvest a consistent surface area of duckweed throughout time and between trays. One square-foot of duckweed from OA3 was introduced to each tray on January 21, 2020. However, the duckweed may have changed in densities as more duckweed was extracted and the remaining duckweed in OA3 spread into the new unoccupied space. The TM tray was exposed to sunlight on the second day, which would have affected the growth rate of the first harvest. Due to the turbidity of wastewater, the pump was prone to clogging, and this affected many data sets throughout the study. A full calendar of events for the harvesting period is provided in Appendix E.

Duckweed was measured for growth using a 5-day harvesting period. At each sampling time, one square-foot of duckweed was harvested from each tray near the effluent pump using a net and placed into a plastic bag. The duckweed was taken back to the lab, dried at 60ºC for 24 hours, the dry mass recorded, and the growth rate calculated. Water temperature was also recorded beginning on the fourth harvest to determine if temperature had an effect on growth rate.

4.3 Results and Discussion

4.3.1 Growth Rate Analysis

After the first several harvests, duckweed production began to steadily increase throughout the end of winter and into springtime as sunlight intensity increased and air temperature rose above the minimum 65°F the greenhouse is maintained at throughout the winter. Figure 12 provides the duckweed harvest results in all four trays, and Table 15 presents the average growth rate in each tray. Each tray is then compared to water temperature in Table 16, and average COD is shown in Table 17. Graphs of water and air temperature by harvest and the periodic measurements of COD can be seen in Appendix E. Also, PPFD measurements can be seen in Appendix E.

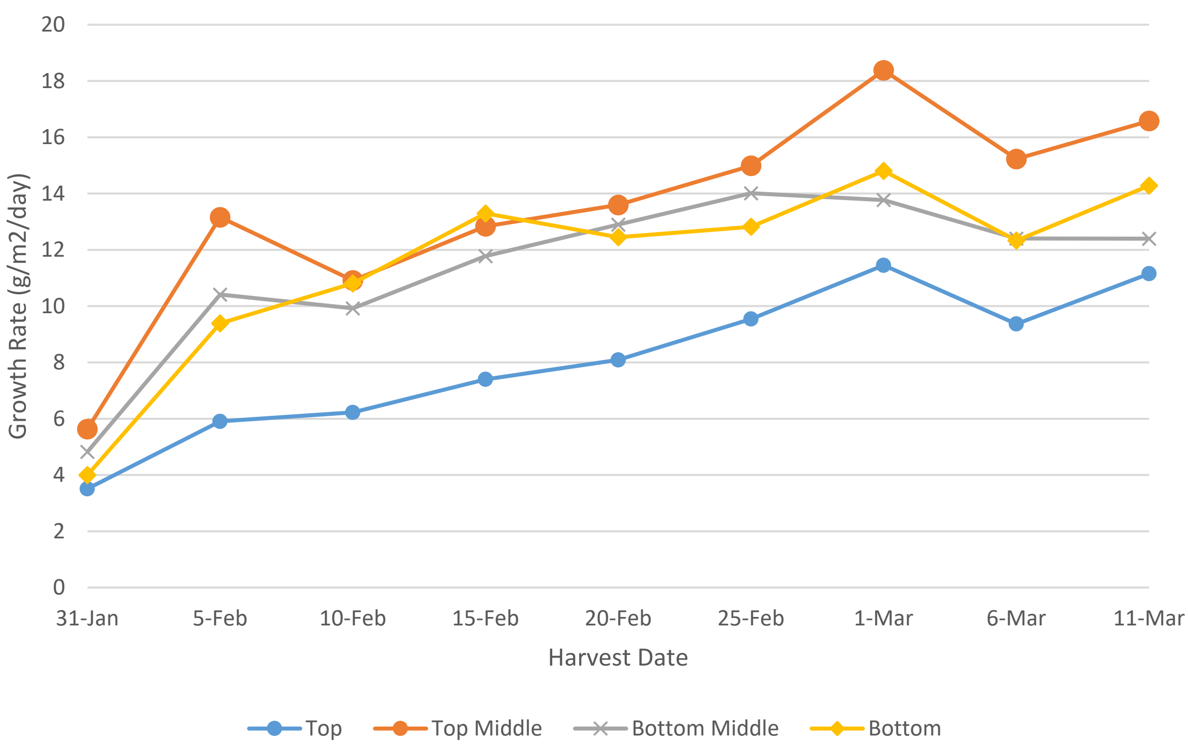

Figure 12: Vertical farming system duckweed growth data for each tray in the system.

Table 15: Average duckweed growth for each tray in the vertical farming system (n = 9).

	Growth rate (g/m^2/day)			
	Top	Top Middle	Bottom Middle	Bottom
Avg.	8.1	13.5	11.4	11.6
St. Dev	2.6	3.7	2.8	3.3

Table 16: Average water temperature by tray (n = 6).

	Water Temperature (°C)			
	Top	Top Middle	Bottom Middle	Bottom
Avg.	19.9	20.2	19.0	15.9
St. Dev.	1.9	2.0	1.4	1.2

Table 17: Soluble COD (sCOD) between OA3 and a combined tray average (n = 4).

	Soluble COD (mg/L)	
	OA3	Trays Avg.
Avg.	38	45
St. Dev.	17	21

Seen in Table 15, water temperature was significantly higher in the top three trays compared to the bottom tray, although, this did not affect growth rates substantially. Soluble COD, shown in Table 16, was slightly higher in the trays than in OA3, but this may be due to variability in sampling and analysis (note the high standard deviation). Because COD measurements were not taken consistently during each harvest, it is difficult to analyze the effects COD has on duckweed growth, especially since growth rates did not stabilize during this study.

The top tray was the slowest-growing tray during the experiment time frame, with the TM tray producing high growth rates for every harvesting period. The bottom and BM tray growth rates were consistently in between the top and TM growth rates. There are several explanations which may explain the production difference between each lighting condition:

- Given the TM tray's exposure to both sunlight and artificial light, it was provided the highest PPFD for a majority of the study.
- Since sunlight intensity from January-March is low, the grow lights outperformed sunlight. The low production observed on the top tray may increase as summer approaches. It is anticipated that the top tray growth rate would increase substantially during the summer because sunlight would dominate light intensity during these months.
- For the three trays exposed to artificial lighting, grow lights were producing heat, raising the air and water temperature to a more suitable environment.
- Grow lights were on 12 hours versus the ~10.5-11 hours of sunlight State College received during the study period.
- The bottom tray had the lowest water temperature during every harvest due to its close proximity to the ground. Despite the lower water temperature, duckweed growth rate was nearly the same between the BM and bottom trays, as both were covered with the black cloth. It can be hypothesized that water temperature has a small effect on growth rate, but one study cannot conclude this.

4.3.2 Measured Duckweed Mass Losses

Throughout the harvesting process, many factors contributed to duckweed losses at various stages between the harvest and final mass measurement:

- During the harvest, it would have taken extensive measures to retrieve every duckweed frond using a net. A high percentage of duckweed was retrieved, but there was a minor, but not negligible, loss.
- When removing the square-foot frame, some duckweed would attach to it and be removed from the tray, causing the next harvest to have less mass and a smaller apparent growth rate.
- When removing the duckweed sample from the container in the lab, some duckweed would attach to the container and would be cleaned off, not making it to the drying stage.
- After drying, duckweed would stick to the drying trays, resulting in another mass loss.
- The duckweed samples were not washed prior to drying, so it is possible that some macroinvertebrates and sludge were included in the mass. This may or may not have offset the losses, but it further contributed to variability from a true duckweed growth rate.

4.3.3 Comparison to 2017 Tray Growth Rate Data

During an experiment conducted in 2017, wastewater from various tanks was pumped through trays to determine duckweed growth in different nutrient levels. The results, shown in Table 18, showed high average growth rates of 6.7 ± 2.3 g/m^2-day in OA3. However, the highest growth rates were from OA1 at 7.8 ± 3.1 g/m^2-day with a maximum of 14.0 g/m^2-day on April 28th.

Table 18: Duckweed growth rates measured in trays fed from water from different tanks in 2017 (Roman, 2017).

Growth rate (g/m²/day)			
	OA1	**OA2**	**OA3**
Average	7.8	6.4	6.7
Std Dev	3.1	2.5	2.3

When comparing data from the 2017 experiment to the vertical farming system data in this study, it can be seen that the top tray had a growth rate of nearly twice the value as OA3 at a similar time of year for each data point. For example, OA3 duckweed production in 2017 during late February was 4.6 g/m^2-day, but results from this study displayed growth rates of 9.5 g/m^2-day in the top tray exposed to natural light: a 105% increase. The primary factor for this difference would be location of the study within the Eco-Machine™ greenhouse. In this study, the top tray was located above most obstructions, providing direct lighting to the trays. However, the 2017 study was conducted near the wall along the entrance door, and the trays were positioned lower to the ground. The wall would block evening sunlight, opening the entrance door may have caused temperature fluctuations in the trays, and shading from OA1 taro plants may have affected growth rates. Lack of evening sunlight caused a significant decrease in growth rates, which makes it difficult to compare growth rates between studies. This analysis provides insight on the importance of the VFS's location within the greenhouse and being conscious of potential obstructions and temperature variations.

4.3.4 Energy Balance Effect

With the addition of four trays and three grow lights, electrical energy was used to operate the lower trays that would otherwise lose a high proportion of growth rate due to lack of light. Three 60W grow lights that are on for 12 hours per day would consume 789 kWh/yr, seen in Calculation 4.1.

$$60\ W * \frac{12\ hrs}{1\ day} * \frac{1\ kW}{1000\ W} * \frac{365\ days}{1\ year} * 3\ LED\ grow\ lights = 789\ {}^{kWh}/_{yr} \qquad (C4.1)$$

This is a substantial amount of energy to operate a vertical farming system. This is nearly 30% of all energy consumption excluding propane usage, with the air compressors responsible for 63% of the total energy usage, down from 91%.

The potential energy production of the duckweed harvested under different lighting conditions is provided in Table 19. In this analysis, a comparison in biofuel production between the coupled process of bioethanol and methane production (10.3 kJ/g) and solely methane production (6.8 kJ/g) is provided based on data presented in Calicioglu and Brennan (2018). Supporting calculations are provided in Appendix E.

Table 19: Theoretical energy production by duckweed grown in different trays of the vertical farming system.

Tray	Avg. Duckweed Yield (St. Dev) (g DW/m^2-day)	Tray Surface Area (m^2)	Bioethanol + Methane (kWh/yr)	Methane (kWh/yr)
Top	8.1 (2.6)	0.38	3.2	2.1
TM	13.5 (3.7)	0.38	5.4	3.5
BM + B	11.5 (2.9)	0.76	9.1	6.0
TOTAL		**1.52**	**17.7**	**11.6**

The amount of theoretical VFS duckweed energy production does not compensate for the energy consumption to power the grow lights. If grow lights were not used, duckweed growth would likely decrease in every tray except the top, but the system would remain net-energy positive, excluding propane usage. As mentioned before, however, the most economic path for duckweed is in agriculture, not biofuel, due to the current market value of protein (Calicioglu, 2019).

4.3.5 Carbon Balance Effect

The addition of growth trays should increase duckweed's impact on carbon removal in the system. Similar to carbon balance estimates of removal in OA3, the clarifier, and pond, Table 20 shows duckweed's increase in theoretical removal of carbon. However, the average of each tray was taken instead of the maximum growth rate for conservative purposes because the growth of duckweed on lower trays may not reach maximum yield due to the lack of direct sunlight.

Table 20: Theoretical carbon removal by duckweed grown in different trays of the vertical farming system.

	A	B	C	D
Tray	Avg. Duckweed Yield (St. Dev) (g DW/m^2-day)	Carbon Content* (%)	Tray Surface Area (m^2)	Avg. Duckweed Yield (St. Dev) (g C/day) **(A*B*C)/100**
Top	8.1 (2.6)	39.1	0.38	1.2 (0.4)
TM	13.5 (3.7)	39.1	0.38	2.0 (0.6)
BM + B	11.5 (2.9)	39.1	0.76	3.4 (0.9)
TOTAL			**1.52**	**6.6 (1.2)**

*Measured carbon content by Kreider et al. (2019) for duckweed in the Living Filter.

Seen from the values in Table 19, duckweed can contribute to the carbon balance by 6.6 ± 1.2 g C/day, as a conservative estimate. If this is added to duckweed carbon removal from the three existing tanks containing it (27.8 g C/day in combination), duckweed can remove 34.4 g C/day. This is about a 24% increase in duckweed carbon removal contributions from a pilot-scale vertical farming system. Significantly larger effects could occur if full-scale duckweed vertical farming systems were implemented at the Eco-Machine™. Table 21 below shows the change in net-carbon yield with the addition of the vertical farming system.

Table 21: Penn State Eco-Machine™ adjusted biological carbon balance including the vertical farming system.

	Net-Carbon Yield (g C/day)	
Component	**2016**	**2019-20**
Net Biological	-21	-38
Duckweed VFS	-6.6	-6.6
Net Carbon	**-28 g C/day**	**-45 g C/day**

The vertical farming system, though a relatively small addition to the Eco-Machine™, makes a noticeable difference on the net-carbon yield of the system because the system is near net-carbon neutral. Although this would make a negligible difference when incorporating propane, heating is not a necessity for many regions where Eco-Machines™ operate. Due to duckweed's high growth rate, a small-scale vertical farming system is able considerably increase the sustainability of the Penn State Eco-Machine™.

4.4 Recommendations and Future Work

Since this experiment was the first trial for a vertical farming system in the Eco-Machine™, there are many avenues for improvement and for expansion of analysis. The VFS was monitored approximately every other day, and periodically the effluent tubing would clog, and wastewater would overflow the trays. When the situation was fixed, duckweed would attach to the wall as the water level decreased back to the original height, and thereby reduce the density of duckweed on the water surface. In future experiments, the VFS should be monitored daily to minimize water level fluctuations due to clogging of tubes.

The parameters monitored during the experiment were water and air temperature, sCOD, and greenhouse PPFD. There are many other parameters that could be collected during a study like this. Many other parameters could have a substantial impact on growth rate, including nitrogen, phosphorous, and other nutrient levels that may affect growth rate. This experiment should be continued until the growth rate stabilizes at a value before concluding the study, and an annual average growth rate should be determined to improve the carbon and energy balance estimates. Unfortunately, this study was concluded prematurely due to the spread of COVID-19, which is why a stabilized growth rate was unable to be achieved.

In future studies, modifying the HRT in the duckweed trays could be investigated to determine if growth rates could be improved. Even though this may not significantly affect the total duckweed yield in the Penn State Eco-Machine™, it could prove to make an impact at both future and existing large-scale ecological wastewater treatment facilities.

In the future, a larger vertical farming system could be implemented in unused space within the greenhouse. A location that could be utilized is space above the pond. If a vertical farming system was built above the pond, the system's total duckweed yield could nearly double. A common size of a "kiddie pool" is about 45" in diameter, which would fit above the pond (D_{pond} = 60"). If three of these containers were stacked vertically similar to the rectangular trays, an additional 3 m^2 of duckweed surface area could be provided. In addition to the 1.5 m^2 of surface area from the current VFS, this would increase total available surface area from 5.35 m^2 to 9.85 m^2 in the Eco-Machine™. Whether unused space is utilized for the addition of another vertical farming system or for a new hydroponics system, the Eco-Machine™ has the potential to provide numerous options to increase its sustainability.

4.5 Conclusion

The Eco-Machine's ability to support a vertical farming system provides access to numerous opportunities for sustainability improvement. High duckweed growths in the VFS are encouraging for duckweed production expansion in the greenhouse. The study's purpose was to verify the effectiveness of vertical duckweed production; growth exceeded results from prior studies conducted during the same time of year, proving its effectiveness and showing that building vertically could increase growth rates compared to studies near ground-level. More studies should occur in the future to analyze duckweed's growth during times of year without data points, which would also provide accurate average growth data for the energy and carbon balance.

5.0 Overall Recommendations and Future Work

The following list summarizes recommendations from the carbon and energy balance, along with the vertical farming system experiment.

- Monitor the solar panels to ensure proper operation. The fluid expansion tracker system can theoretically increase solar production by 25% at full capacity, but it must be adjusting to point to the sun properly.
- Record the energy production by the solar array on the inverter to find monthly average production rates. This will not only help determine the effectiveness of the solar array but also ensure the array is working properly.
- Inspect the Eco-Machine™ greenhouse for leaks to decrease propane consumption for heating.
- Install a dissolved oxygen control system to reduce air compressor energy consumption.
- In future carbon balance analyses, consider internal and external recycle flow rates.
- Measure COD and CBOD in wastewater arriving at the Eco-Machine™. Also, investigating the carbon flow path for non-biological (recalcitrant) carbon flow would significantly improve the accuracy of the carbon balance.
- Investigate the use of C-13 to determine accurate plant growth rates.
- There are many alternative uses for by-products that should be considered at the Eco-Machine™ and at all other Eco-Machines™:
    - Digest plant litter and duckweed to produce methane that can be used for heating the greenhouse.

  - Ferment duckweed to produce ethanol and put the remaining duckweed solids into an anerobic digester with sludge and plant litter to produce methane.
  - Use duckweed and plant litter for fertilizer/soil amendment on-site.
  - Use duckweed as a protein supplement for animals.
  - If an aquaponics system is installed in the future, duckweed can be used to feed the fish in the system.
- Continue to monitor duckweed growth for a full calendar year to determine an average annual duckweed growth rate in the vertical farming system and in OA3 wastewater.
- As stated in the vertical farming system (VFS) recommendations, duckweed growth rates should be tested at different flow rates. Different HRTs may be able to increase growth rates noticeably.
- When experimenting with a VFS, limit clogs and overflows, as this can affect growth rates in numerous ways.
- The VFS could be expanded to other areas in the greenhouse at a larger scale to improve the sustainability of the facility.
- In future VFS studies, measure different water quality parameters such as phosphorus and nitrogen to provide more insight to important wastewater conditions for duckweed growth.

6.0 Overall Conclusion

The Penn State Eco-Machine™, given its small scale, was not designed to optimize wastewater treatment efficiency. It was designed to further research, provide educational opportunities, and support sustainability awareness in the Penn State community. The Penn State Eco-Machine™, although pilot-scale, shows promising potential for improvement. Given its relative size, larger-scale Eco-Machines™ could perform at higher efficiencies and operate completely off-grid if maintained properly. The electrical input necessary for an Eco-Machine™ can be provided by a reasonable amount of on-site solar panels. In larger settings where there is a higher surface area of water, byproducts such as duckweed can also provide biofuel to the system if necessary, or the byproducts can be supplied to the local bioeconomy. Ecological wastewater treatment methods reduce carbon emissions significantly in many cases. If the Penn State Eco-Machine™ would not need propane for heating, it would store more carbon than it is releasing and would produce more energy than it consumes.

The pilot-scale vertical farming system experiment proved to produce higher growth rates with the use of LED grow lights during colder months. However, the theoretical embodied energy in the duckweed did not compensate for the power required to operate the system. Fortunately, the market value of duckweed in the agricultural sector provides more opportunities and a higher return on investment (Calicioglu, 2019). Even though the energy consumption from the grow lights would cause the energy balance to switch to net-energy negative, the overall sustainability of the Eco-Machine™ could increase with higher duckweed yield. As seen this study, Eco-Machines™ are a promising alternative to wastewater treatment, especially in regions where heating the greenhouse would not be necessary for operation.

Appendix A: Eco-Machine™ Images

Figure A1: The Penn State Eco-Machine™ Greenhouse

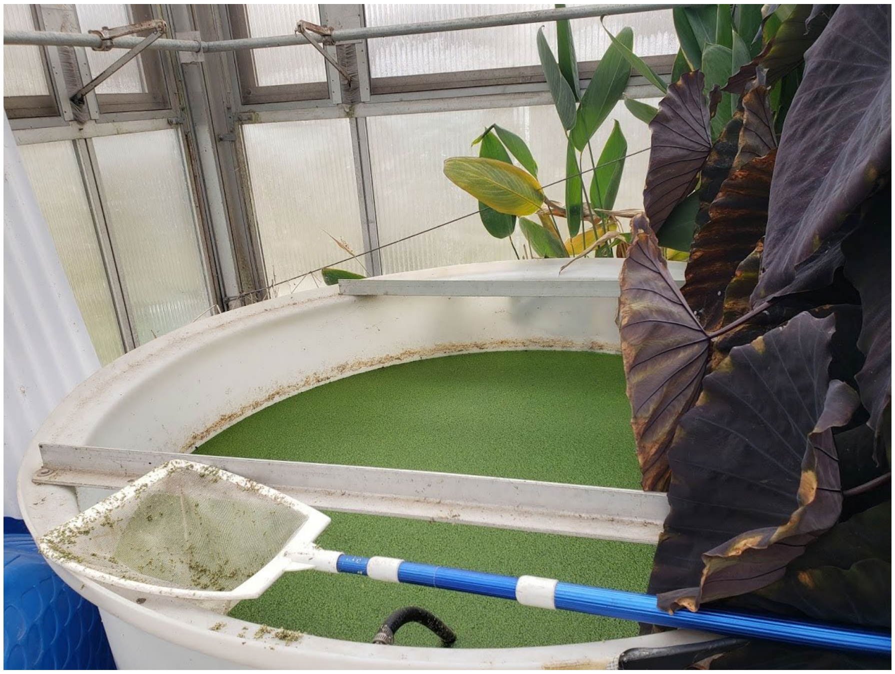

Figure A2: Open Aerobic Tank 3 (OA3)

Figure A3: Clarifier

Figure A4: Pond

Appendix B: Eco-Machine™ Flora

Figure A5: Canna Lily (*Roi humbert*)

Figure A7: Black Magic Taro (*Colocasia esculenta*)

Figure A6: Calla Lily (*Zantedeschia aethipica*)

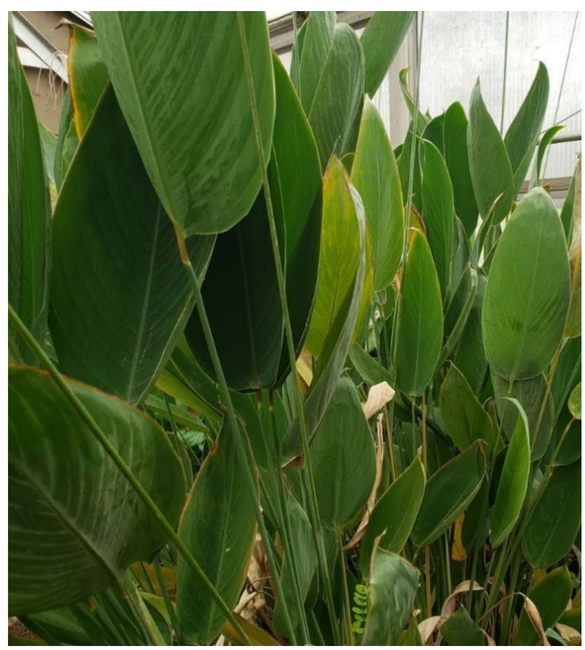

Figure A8: Water Canna (*Thalia dealbata*)

Appendix C: Energy Balance

Table A1: Duckweed Growth Data in Different Tanks (Roman, 2017)

	Date	Growth rate (g/m²/day) OA1	OA2	OA3
	Jan. 24*	*3.0*	*2.3*	*3.4*
	Jan. 31	2.7	2.8	2.9
	Feb. 7	3.5	3.4	3.5
	Feb. 14	4.6	3.5	3.4
	Feb. 21	5.0	3.8	4.4
	Feb. 28	6.0	4.0	4.6
	Mar. 7	6.2	5.1	5.0
	Mar. 14	7.8	6.0	5.1
First 5-day harvest	**Mar. 19**	9.0	7.1	6.7
	Mar. 24	9.8	7.7	6.6
	Mar. 29	8.9	7.6	6.1
	Apr. 3	8.9	6.8	5.9
	Apr. 8	9.7	7.4	6.5
	Apr. 13	12.5	8.8	8.0
	Apr. 18	12.7	11.8	8.0
	Apr. 23	13.1	10.8	10.1
1/2 of duckweed now harvested	**Apr. 28**	14.0	11.8	8.2
	May 3	7.9	7.4	8.3
	May 8	7.0	6.3	7.3
	May 13	7.0	6.4	8.0
	May 18	7.6	6.4	9.4
	May 23	7.1	6.1	9.0
	May 28	6.4	5.4	9.9
	Avg.	7.8	6.4	6.7
	St. Dev	3.1	2.5	2.3

**Samples not washed prior to drying*

Table A2: Inverter Readings 2018-2020

Date	Total Lifetime Generation (kWh)
10/5/2018	18990
10/26/2018	19095
11/7/2018	19131
11/14/2018	19161
9/27/2019	21123
10/11/2019	21197
10/15/2019	21230
10/25/2019	21286
11/8/2019	21334
11/21/2019	21392
12/6/2019	21422
12/13/2019	21444
12/17/2019	21445
1/13/2020	21517
1/16/2020	21528
1/21/2020	21548
1/26/2020	21563
1/30/2020	21571
2/2/2020	21580
2/9/2020	21597
2/17/2020	21619
2/20/2020	21636
3/1/2020	21703
3/6/2020	21728
3/29/2020	21867

	Table A3: 2018-20 Propane Consumption Data	
	Date	**# of gallons**
2017-18 Winter (Incomplete)	**1/25/2018**	84.4
	2/14/2018	163.9
	3/13/2018	182.8
	3/15/2018	23.4
	3/27/2018	80.8
	4/9/2018	57.8
	4/17/2018	35.1
	4/27/2018	39.6
2018-19 Winter	**9/5/2018**	21.3
	11/2/2018	75.4
	11/17/2018	86.8
	11/30/2018	85.4
	12/13/2018	109.7
	12/18/2018	34.3
	12/26/2018	52.2
	1/7/2019	67.7
	1/16/2019	84.3
	1/21/2019	57.9
	1/30/2019	72.9
	2/6/2019	53.6
	2/13/2019	50.1
	2/25/2019	77.6
	3/4/2019	52.5
	3/13/2019	51.0
	3/26/2019	64.9
	4/11/2019	23.4
	4/23/2019	35.8
2019-20 Winter (Incomplete)	**10/21/2019**	40.8
	11/19/2019	63.0
	12/3/2019	65.9
	12/17/2019	97.9
	12/31/2019	92.5
	1/14/2020	82.9
	1/28/2020	111.1
	2/11/2020	76.7
	2/25/2020	85.5
	3/10/2020	75.1

Energy Production Calculations

Solar Array Interpolation:

$$Daily\ Avg\ = \frac{I_p - I_n}{No.\ of\ days\ between\ readings}$$

$$I_o = I_p + (Daily\ Avg * No.\ of\ days\ to\ 1st\ of\ the\ month)$$

$$I_o = 1st\ of\ the\ Month\ Reading$$

$$I_p = Last\ inverter\ Reading\ of\ the\ next\ month$$

$$I_n = First\ Inverter\ Reading\ of\ the\ next\ month$$

OA3 Duckweed Energy Production (calculation shown in text):

$$2.31\ m^2 * \frac{\frac{10.1\ g}{m^2}}{day} * \frac{10.3\ kJ}{g} * \frac{1\ kWh}{3.6 * 10^3 kJ} * \frac{365\ days}{1\ yr} = 24.4 \frac{kWh}{yr}$$

Clarifier Duckweed Energy Production:

$$0.82\ m^2 * \frac{\frac{10.1\ g}{m^2}}{day} * \frac{10.3\ kJ}{g} * \frac{1\ kWh}{3.6 * 10^3 kJ} * \frac{365\ days}{1\ yr} = 10.9 \frac{kWh}{yr}$$

Pond Duckweed Energy Production:

$$1.82\ m^2 * \frac{\frac{10.1\ g}{m^2}}{day} * \frac{10.3\ kJ}{g} * \frac{1\ kWh}{3.6 * 10^3 kJ} * \frac{365\ days}{1\ yr} = 19.2 \frac{kWh}{yr}$$

Energy Consumption Calculations

Humidifier: 84 W, 99% efficiency (neglect)

$$\frac{84\ J}{s} * \frac{3600\ s}{1\ hr} * \frac{8\ hr}{1\ day} * \frac{60\ days}{1\ yr} * \frac{1\ kWh}{3.6 * 10^6 J} = 41 \frac{kWh}{yr}$$

Air Compressor Consumption: 0.75 hp, 8 hrs/day operation, 81% efficiency

$$0.56\ kW * \frac{8\ hrs}{1\ day} * \frac{365\ days}{1\ yr} = 1635 \frac{kWh}{yr}$$

$$Energy\ Waste = Consumption * \frac{100\% - Efficiency\ (\%)}{100\%}$$

$$Energy\ Waste = 1635 \frac{kWh}{yr} * \frac{100\% - 81\%}{100\%} = 311 \frac{kWh}{yr}$$

Internal Recycle Pump: 1 hp, 16 min/day operation, 75% efficiency

$$0.75\ kW * \frac{16\ min}{1\ day} * \frac{1\ hr}{60\ min} * \frac{365\ days}{1\ yr} = \frac{kWh}{yr}$$

$$Energy\ Waste = 1635 \frac{kWh}{yr} * \frac{100\% - 81\%}{100\%} = 311 \frac{kWh}{yr}$$

External Holding Tank Pump (calculation shown in text): 0.5 hp, 75% efficiency

$$0.37\ kW * \frac{16\ min}{1\ day} * \frac{1\ hr}{60\ min} * \frac{365\ days}{1\ yr} = 48 \frac{kWh}{yr}$$

Eco-Machine™ Propane Usage Calculations:

2018-19 Winter = Σ (All propane numbers from winter) = <u>1156.8 gallons</u>

2019-20 Winter = Σ (Propane usage from 10/21/2019 to 3/10/2020 + average propane usage past 3/10 from the previous two winters)

NOTE: As seen in Table A.3, the last date of propane consumption data collected was 3/10/2020, thus the need for extrapolation.

Average propane usage past 3/10:

2017-2018 Winter = Σ (Propane usage from 3/13/2018 to 4/27/2018) = 236.7 gallons

2018-2019 Winter = Σ (Propane usage from 3/13/2019 to 4/23/2019) = 175.1 gallons

2019-20 Winter = Σ (791.4 + $\frac{236.7+175.1}{2}$) = <u>997.3 gallons</u>

Average of 2018-19 and 2019-20 winter (both underlined above) = **<u>1077.1 ± 79.8 gallons/year</u>**

Appendix D: Carbon Balance

Table A4: Penn State Eco-Machine™ 2016 COD Measurements

Row groups: Summer – No students (18-Jul-16 to 22-Aug-16); Internal recycle OFF (23-Sep-16 to 4-Nov-16); Internal recycle ON (11-Nov-16 to 9-Dec-16)

Date	COD (mg/L)									
	Truck	*Holding*	*Influent*	*CA1*	*CA2*	*OA1*	*OA2*	*OA3*	*Clarifier*	*Pond*
18-Jul-16	254.6	92.1	-	57.1	57.1	34.5	18.7	22.1	24.3	14.1
25-Jul-16	188.0	60.4	-	57.1	44.2	37.3	23.5	25.2	-	15.9
1-Aug-16	224.2	93.2	218.5	57.1	41.2	31.5	22.8	20.7	20.4	13.6
7-Aug-16	-	341.6	359.6	179.0	164.3	65.9	34.9	29.7	29.2	10.9
22-Aug-16	157.5	88.7	156.4	175.6	89.8	39.6	34.1	37.7	31.8	12.5
23-Sep-16	260.3	131.6	275.0	87.5	60.4	43.9	25.2	32.9	32.4	7.2
7-Oct-16	267.1	180.1	-	136.1	112.4	47.7	38.6	37.4	30.5	18.1
28-Oct-16	240.0	146.2	167.7	133.8	107.9	36.4	28.5	25.6	25.0	15.6
4-Nov-16	259.2	168.8	202.7	162.1	136.1	45.0	31.5	29.9	29.5	18.7
11-Nov-16	268.2	151.9	245.6	110.1	68.3	32.7	28.0	22.9	30.3	14.7
18-Nov-16	276	190	312	143	83	67	30	27	25	16
2-Dec-16	254	165	296	136	72	41	32	25	31	17
9-Dec-16	215	156	-	149	67	43	35	29	27	12
Average	**238.6**	**151.3**	**248.2**	**121.8**	**84.9**	**43.5**	**29.4**	**28.0**	**28.0**	**14.4**
St. Dev.	**36.1**	**69.9**	**68.4**	**44.2**	**36.5**	**11.4**	**5.7**	**5.4**	**3.7**	**3.2**

Table A5: Penn State Eco-Machine™ 2019-20 COD Measurements

Row groups: Summer - No students (7-Jun-19 to 26-Jul-19); Internal recycle ON (1-Oct-19 to 14-Jan-20)

Date	COD (mg/L)							
	Truck	*CA1*	*CA2*	*OA1*	*OA2*	*OA3*	*Clarifier*	*Pond*
7-Jun-19	323.0	-	-	-	-	-	-	-
21-Jun-19	201.0	-	-	-	-	-	-	-
2-Jul-19	102.0	-	-	-	-	-	-	-
26-Jul-19	458.0	-	-	-	-	-	-	-
1-Oct-19	118.0	-	-	-	-	-	-	-
15-Oct-19	336.0	-	-	-	-	-	-	-
29-Oct-19	420.0	166.0	150.0	106.0	80.0	76.0	78.0	32.0
12-Nov-19	440.0	118.0	140.0	100.0	92.0	86.0	62.0	35.0
26-Nov-19	226.0	138.0	110.0	74.0	66.0	51.0	42.0	21.0
10-Dec-19	628.0	150.0	132.0	92.0	76.0	75.0	47.0	28.0
14-Jan-20	400.0	436.0	434.0	286.0	126.0	103.0	69.0	10.0
Average	**332.0**	**201.6**	**193.2**	**131.6**	**88.0**	**78.2**	**59.6**	**25.2**
St. Dev.	**159.6**	**132.2**	**135.4**	**87.1**	**23.2**	**18.9**	**15.0**	**10.0**

Table A6: Penn State Eco-Machine™ Average Carbon Flow				
	2016 Carbon Flow (g C/day)		2019-20 Carbon Flow (g C/day)	
	Average	Standard Deviation	Average	Standard Deviation
Truck	189.7	28.7	150.8	72.5
CA1	48.4	17.5	91.6	60.0
CA2	33.7	14.5	87.8	61.5
OA1	17.3	14.5	59.8	39.6
OA2	11.7	2.3	40.0	10.5
OA3	11.1	2.2	35.5	8.6
Clarifier	11.1	1.5	27.1	6.8
Pond	5.7	1.3	11.4	4.5

Carbon Balance Calculations:

Loading rate of carbon in the wetland is in g COD/m^2-day:

Clarifier concentration: 59.6 mg COD/L (2019-20) 28.0 mg COD/L (2016)

Wetland surface area: 52.0 m^2

$$2016: \frac{28.0\ mg\ COD}{L} * \frac{1\ g\ COD}{1000\ mg\ COD} * \frac{3.785\ L}{1\ Gal} * \frac{700\ Gal}{Day} * \frac{1}{52.0\ m^2}$$
$$= 1.43\ {}^{g\ COD}/_{m2-day}$$

$$2019-20: \frac{59.6\ mg\ COD}{L} * \frac{1\ g\ COD}{1000\ mg\ COD} * \frac{3.785\ L}{1\ Gal} * \frac{400\ Gal}{Day} * \frac{1}{52.0\ m^2}$$
$$= 1.74\ {}^{g\ COD}/_{m2-day}$$

Growth Rate of Calla Lily:

$$6.43\ {}^{\mu mol\ O_2}/_{m^2 s} * \frac{86{,}400\ s}{1\ day} * \frac{1\ mol\ O_2}{10^6\ \mu mol\ O_2} * \frac{32\ g\ O_2}{1\ mol\ O_2} \frac{2\ mol\ WW}{25\ mol\ O_2} * \frac{10\ mol\ C}{1\ mol\ WW} * \frac{12\ g\ C}{1\ mol\ C}$$
$$* \frac{1000\ mg\ C}{1\ g\ C} = 6.67\ {}^{g\ C}/_{m2-day}$$

Growth Rate of Canna Lily:

$$13.2\ {}^{g\ DW}\!\Big/_{m^2 - day} * \frac{42.7\%\ C}{100\%\ DW} * \frac{0.90\ m^2}{1} = 5.6\ {}^{g\ C}\!\Big/_{m2 - day}$$

Growth Rate of Water Canna:

$$8.49\ {}^{g\ DW}\!\Big/_{m^2 - day} * \frac{45.7\%\ C}{100\%\ DW} * \frac{1.08\ m^2}{1} = 4.2\ {}^{g\ C}\!\Big/_{m2 - day}$$

Plant Litter Alternative Estimation

The half-life of carbon in plants similar to the species at the Eco-Machine™ ranges from 0.6 to 2 years (Catalán et. al., 2016). Since this range is so large, determining the decay rate in terms of natural decay instead of half-life can give a more precise measurement. Natural decay is based off the following formula:

$$A = Pe^{-kt}$$

where P is the initial mass and A is the resultant mass as a function of time, and *k* representing the decay constant. In temperate regions, a study determined that an average *k*-value across numerous temperate climates is 0.36 yr^{-1} (Aerts, 1997). Given this decay constant, a leaf would decay to roughly 15% of its original composition after five years. Since carbon decay is not linear, the rate of decay will be estimated as linear at which the line of decay reaches 85% with a k-value of 0.36 yr^{-1}. At the point 85% has decayed, it will be assumed 100% has been decayed because some plant litter will be buried and stored for a much longer period. With $k = 0.36\ yr^{-1}$, the time needed to reach 85% decay is 5.27 years.

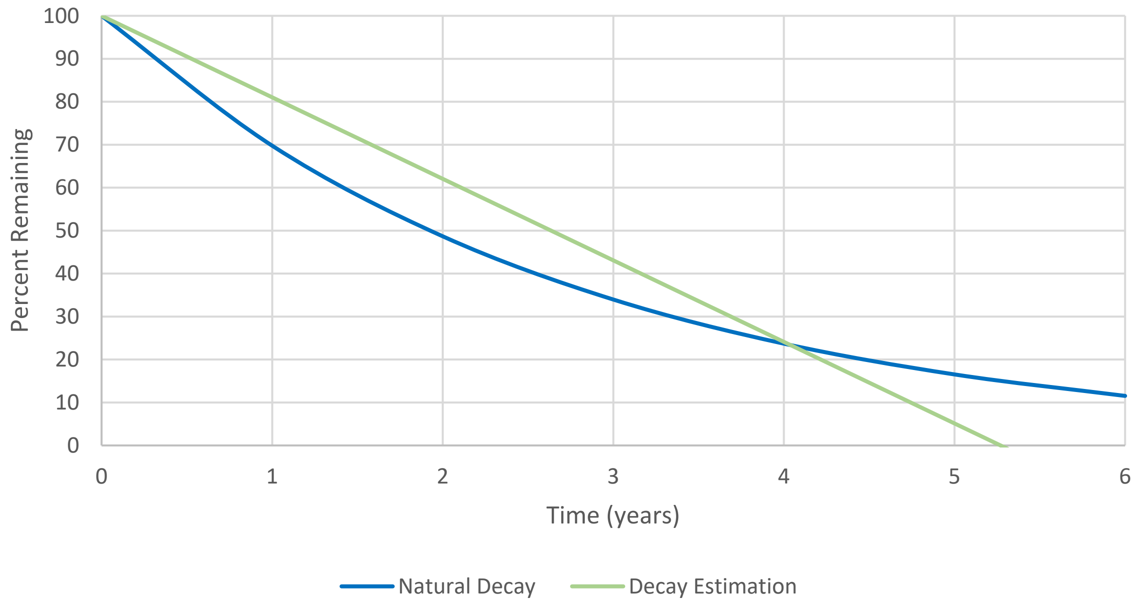

Figure A9: Natural Plant Litter Decay Estimation

Appendix E: Duckweed Vertical Farming System

Table A7: Vertical Farming System Duckweed Growth Data								
	Dry Density (g/ft^2)				Growth rate (g/m^2/day)			
Date	**Top**	**Top Middle**	**Bottom Middle**	**Bottom**	**Top**	**Top Middle**	**Bottom Middle**	**Bottom**
31-Jan	3.2610	5.2302	4.4801	3.9090	3.5	5.6	4.8	4.0
5-Feb	2.7435	6.1123	4.8365	4.3621	5.9	13.2	10.4	9.4
10-Feb	2.8910	5.0694	4.6087	5.0208	6.2	10.9	9.9	10.8
15-Feb	3.4372	5.9630	5.4705	6.1753	7.4	12.8	11.8	13.3
20-Feb	3.7574	6.3161	5.9903	5.7830	8.1	13.6	12.9	12.4
25-Feb	4.4332	6.9625	6.5092	5.9548	9.5	15.0	14.0	12.8
1-Mar	5.3198	8.5377	6.3960	6.8781	11.5	18.4	13.8	14.8
6-Mar	4.3506	7.0745	5.7606	5.7280	9.4	15.2	12.4	12.3
11-Mar	5.1805	7.7015	5.7584	6.6346	11.2	16.6	12.4	14.3
Avg.	3.930	6.552	5.534	5.605	8.1	13.5	11.4	11.6
St. Dev	0.944	1.132	0.747	0.996	2.6	3.7	2.8	3.3

Table A8: Vertical Farming System Parameter Data						
	Water Temperature (°C)					
Date	**Top**	**Top Middle**	**Bottom Middle**	**Bottom**	**Air Temperature (°C)**	**Greenhouse PPFD (µmol/m^2/s)**
31-Jan	-	-	-	-	-	-
5-Feb	-	-	-	-	-	-
10-Feb	-	-	-	-	23.8	-
15-Feb	19.15	19.08	17.14	14.14	29.9	-
20-Feb	18.6	18.5	17.6	14.7	18.8	176
25-Feb	19.3	20.1	19.8	16.9	17.9	7
1-Mar	23.8	24.1	20.9	16.9	20.3	185
6-Mar	19.2	19.3	19.1	16.2	23.3	26
11-Mar	19.2	19.9	19.3	16.6	21.0	-
Avg.	19.9	20.2	19.0	15.9	21.1	-
St. Dev	1.9	2.0	1.4	1.2	3.7	-

Table A9: Soluble COD (sCOD) (mg/L)					
	Sampling Location				
Date	OA3	Top	Top-Middle	Bottom-Middle	Bottom
28-Jan-20	30	48	34	28	25
11-Feb-20	14	22	15	14	29
25-Feb-20	55	Combined: 76			
10-Mar-20	52	Combined: 50			

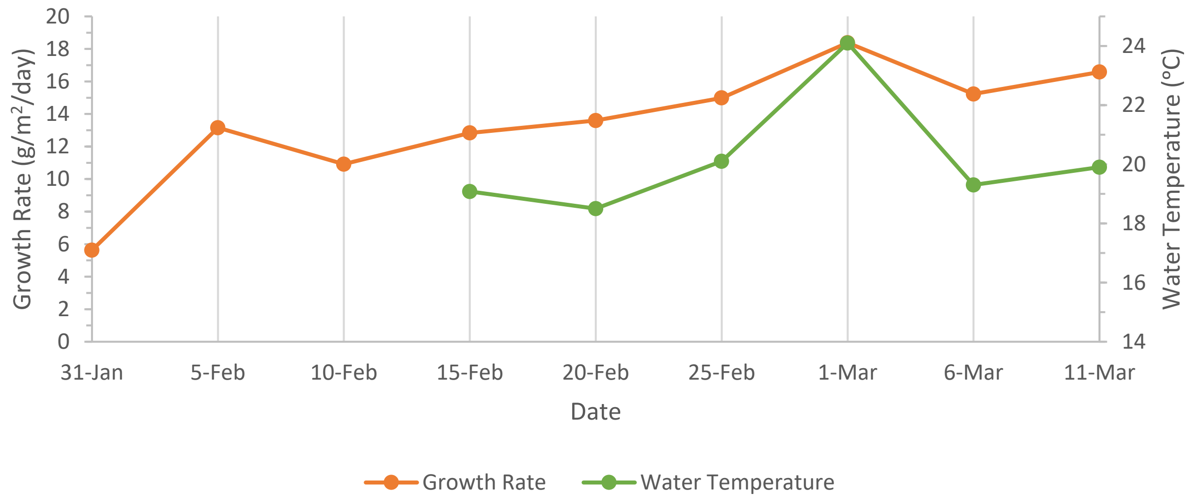

Figure A10: Top tray duckweed growth rate and water temperature.

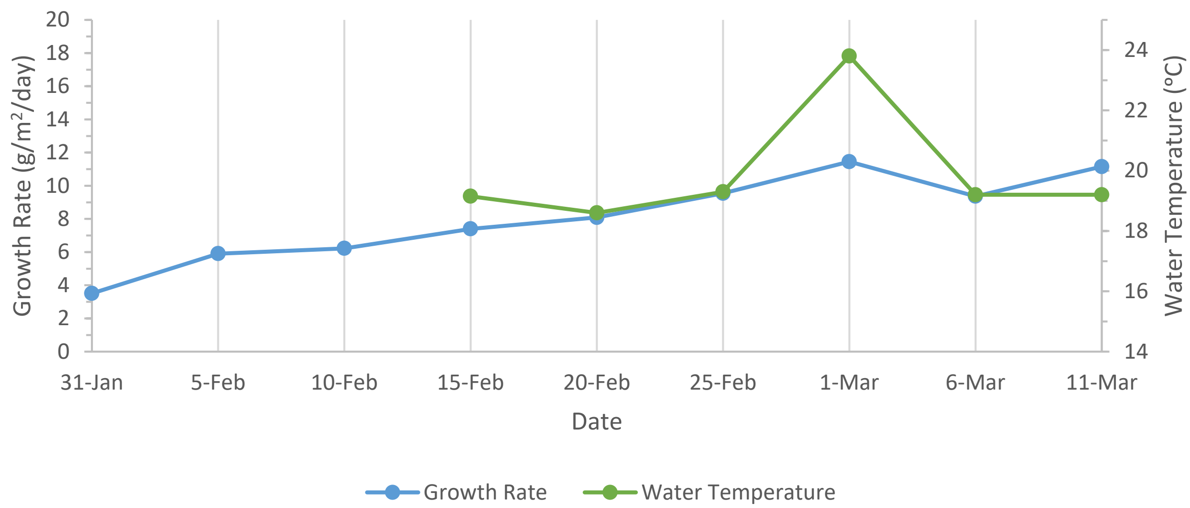

Figure A11: Top middle tray duckweed growth rate and water temperature.

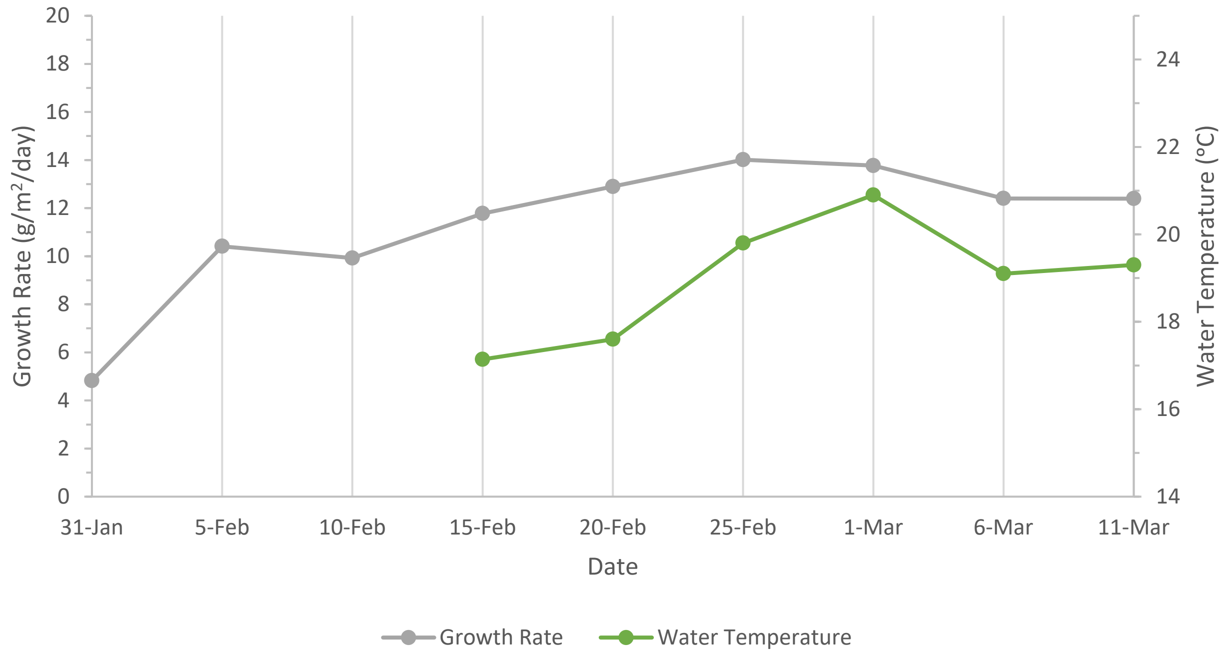

Figure A12: Bottom middle tray duckweed growth rate and water temperature.

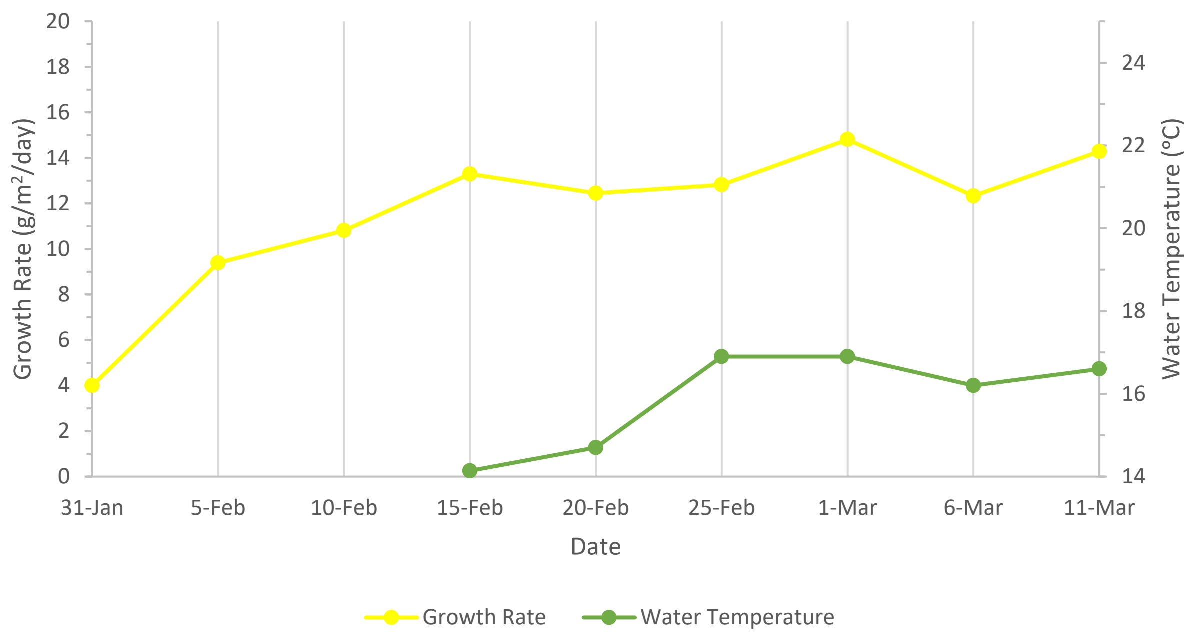

Figure A13: Bottom tray duckweed growth rate and water temperature.

Duckweed Energy Production Calculations:

Top Tray: Average growth rate = 8.1 ± 2.6 g DW/m^2-day, Surface area = 0.38 m^2

Coupled Bioethanol + Methane: 10.3 kJ/g

$$0.38\ m^2 * \frac{8.1\ g}{m^2 * day} * \frac{10.3\ kJ}{g} * \frac{1\ kWh}{3.6 * 10^3 kJ} * \frac{365\ days}{1\ yr} = 3.2\ \frac{kWh}{yr}$$

Only Methane: 6.8 kJ/g

$$0.38\ m^2 * \frac{8.1\ g}{m^2 * day} * \frac{6.8\ kJ}{g} * \frac{1\ kWh}{3.6 * 10^3 kJ} * \frac{365\ days}{1\ yr} = 2.1\ \frac{kWh}{yr}$$

Top-Middle Tray: Average growth rate = 13.5 ± 3.7 g DW/m^2-day, Surface area = 0.38 m^2

Coupled Bioethanol + Methane: 10.3 kJ/g

$$0.38\ m^2 * \frac{13.5\ g}{m^2 * day} * \frac{10.3\ kJ}{g} * \frac{1\ kWh}{3.6 * 10^3 kJ} * \frac{365\ days}{1\ yr} = 5.4\ \frac{kWh}{yr}$$

Only Methane: 6.8 kJ/g

$$0.38\ m^2 * \frac{13.5\ g}{m^2 * day} * \frac{6.8\ kJ}{g} * \frac{1\ kWh}{3.6 * 10^3 kJ} * \frac{365\ days}{1\ yr} = 3.5\ \frac{kWh}{yr}$$

Bottom-Middle + Bottom Tray: Average growth rate = 11.5 ± 2.9 g DW/m^2-day,

Surface area = 0.76 m^2

Coupled Bioethanol + Methane: 10.3 kJ/g

$$0.76\ m^2 * \frac{11.5\ g}{m^2 * day} * \frac{10.3\ kJ}{g} * \frac{1\ kWh}{3.6 * 10^3 kJ} * \frac{365\ days}{1\ yr} = 9.1\ \frac{kWh}{yr}$$

Only Methane: 6.8 kJ/g

$$0.76\ m^2 * \frac{11.5\ g}{m^2 * day} * \frac{6.8\ kJ}{g} * \frac{1\ kWh}{3.6 * 10^3 kJ} * \frac{365\ days}{1\ yr} = 6.0\ \frac{kWh}{yr}$$

Duckweed Harvesting Calendar:

2020 January

MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY	SUNDAY
30	31	01	02	03	04	05
06	07	08	09	10	11	12
13	14	15	16	17	18	19
20	21 Duckweed placed in trays	22 Top Middle tray exposed to sunlight	23 Pumps turned off for 5 hours, overflow in top-middle and bottom	24 Pumps turned off for 12 hours overnight	25	26
27	28	29	30	31 Harvest #1	01	02
03	04	Notes: Green: Duckweed Harvest; Time TBD				

2020 February

MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY	SUNDAY
27	28	29	30	31	01	02
03	04	05 Harvest #2	06	07	08 Pumps turned off for 24 hours, overflow in bottom-middle	09
10 Harvest #3	11	12	13	14	15 Harvest #4	16
17	18	19	20 Harvest #5	21	22	23
24	25 Harvest #6	26	27 Overflow in Bottom middle tray	28	29	01
02	03	Notes: Green: Duckweed Harvest; Time TBD				

2020 March

MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY	SUNDAY
24	25	26	27	28	29	01 Harvest #7, Overflow in top tray
02	03	04	05	06 Harvest #8	07	08
09	10	11 Harvest #9 FINAL HARVEST	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30	31	Notes: Green: Duckweed Harvest				

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Education

Bachelor of Science in Civil Engineering with Honors May 2020
Schreyer Honors College
The Pennsylvania State University, University Park, PA
Structural Engineering Specialization

Study Abroad:

- Universidad de Navarra: Tecnun; San Sebastián, Spain May 2018
  - For two weeks, I studied engineering design at the University of Navarra located in the Basque country of Spain with students from Penn State led by local professors.
- Monash University; Melbourne, Australia Feb-July 2019
  - Took four core engineering courses while attending. It was rigorous study at one of the top universities in Australia and consistently top 100 in the world.

Research

Aug. 2019-April 2020

Senior Honors Thesis: A systematic carbon and energy balance of the Penn State Eco-Machine™ and the implementation of a vertical farming system to increase production of duckweed.

Work Experience

Dawood Engineering, Inc. Harrisburg, PA, USA
Civil Engineering Intern Dec 2017- Feb 2019

- Primarily highway department, while also helping with traffic and structures. Learned to use MicroStation and have experience in important aspects of engineering communication and surveying.

PennDOT Harrisburg, PA, USA
Civil Engineering Intern June-August 2017

- Intern with the traffic unit of Engineering District 8-0. It mainly consisted of field work, including checking road sign quality, understanding the process of line painting, and other aspects of road design.

Leadership and Activities

Bowling Club
Secretary 2016-Present

- Travel approximately ten times a year around the northeast and central USA for tournaments. Also a member of the Virginia Tech bowling team, and I have thrown two perfect 300 games, along with two appearances to the high school PA State Championships.

Curling Club at Penn State 2018-Present

- Competitively travelled to curl and participated in the Penn State curling league.

Tennis Team 2018

- At Penn State-Harrisburg, played number one singles and played number two doubles.

Exams and Technical Skills

- MicroStation, AutoCAD, Revit, SolidWorks, Civil3D, CREO, C++, MATLAB
- Courses: Design of Steel and Timber Structures, Foundation Design, Concrete Design, Advanced Structural Design

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Awards and Honors

- Valedictorian: Middletown Area High School 2016
- Dean's List: All Semesters
- Bill and Betty Fox Scholarship- 2016
- Scholarship for Talented Students: 2018 and 2019
- Kinsey Honors Scholarship Fund: 2018 and 2019
- Intercollegiate Tennis Association Scholar-Athlete: 2018