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Research article

Coupling ecological wastewater treatment with the production of livestock feed and irrigation water provides net benefits to human health and the environment: A life cycle assessment

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ABSTRACT

Ecologically designed wastewater treatment systems (ex., Eco-Machines™) utilize a diverse ecosystem to treat wastewater to the same extent as conventional treatment, but require less energy and chemical inputs. The environmental benefits of Eco-Machines™ can be theoretically maximized by incorporating hyperaccumulating aquatic plants (ex., duckweed) to facilitate nutrient recovery and conversion into protein-rich biomass, which can then be harvested for a range of agricultural and bioenergy applications. Although it has been established that ecological wastewater treatment systems are more cost- and energy-efficient than conventional wastewater treatment systems, a systematic life cycle assessment (LCA) of an Eco-Machine™ coupled with its beneficial by-products has not been conducted. In this study, a series of LCAs were performed on different operational scenarios for a 1000 gallon per day, pilot-scale Eco-Machine™ that, in addition to producing irrigation-quality water, also produces duckweed biomass for aquaculture. The analysis revealed that Eco-Machines™ located in warm climates, which do not require a greenhouse or supplemental heating, use approximately a third of the energy and produce half of the greenhouse gas emissions compared to conventional wastewater treatment systems in similar locations, while also providing benefits to human health, ecosystem quality, climate change, and resources. In addition, increasing the growth area for duckweed using vertical farming techniques improves the overall impact of the system. This study suggests that with proper management, ecological wastewater treatment systems that upcycle nutrients and water into beneficial products can provide a net benefit to human health and the environment.

1. Introduction

Biological wastewater treatment is the most common form of sewage treatment in the developed world and has gone mostly unchanged since the early 1900s. In a conventional wastewater treatment system, organic material and nutrients are typically removed from the wastewater by bacteria that grow in a large aerated/mixed tank (activated sludge tank). Although there are many possible configurations, the wastewater typically then proceeds to an anoxic tank, where denitrifying bacteria reduce nitrate to nitrogen gas. Although effective, conventional wastewater treatment systems require large amounts of energy to operate, and essentially waste a valuable source of nitrogen by letting it escape into the atmosphere. In the U.S. alone, wastewater treatment was responsible for 1.8% (69.4 billion kWh) of the total electricity use in 2011 (Copeland and Carter, 2017), and released approximately 600,000 tons of aqueous total nitrogen (TN) and 300,000 tons of nitrous oxide (N_2O, a greenhouse gas that is 300 times more potent than CO_2) into the environment (Maupin and Ivahnenko, 2011; US EPA, 2012).

As a sustainable, decentralized alternative to conventional wastewater treatment, ecological wastewater treatment systems (ex., Eco-Machine™) utilize a series of tanks containing a variety of microorganisms, macroinvertebrates, and plants to treat wastewater and recover nutrients, all with no chemical input. These systems have been implemented predominantly for treating domestic sewage in small, ecologically conscious communities around the world (ex., EcoVillage Findhorn, 2007). More recently, 'tidal-flow' Living Machines® are being used in major urban office buildings, military bases, housing developments, resorts, and institutional campuses (McNair, 2009). Although there has been little reporting on the implementation of advanced ecological engineered systems in the developing world, the

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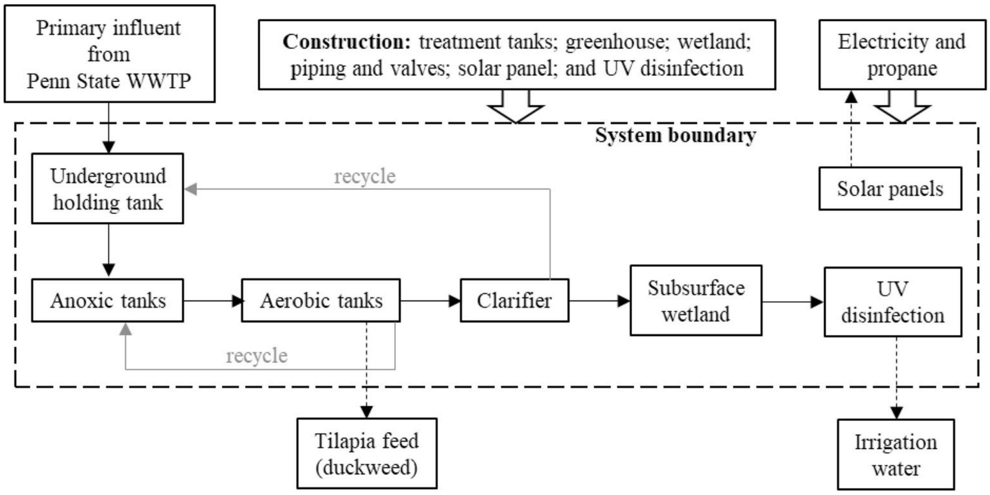

Fig. 1. Schematic of the Penn State Eco-Machine™ and scope of the LCA analysis. Solid arrows indicate the flow of wastewater through the treatment system. Dashed arrows indicate products. The dashed line is the system boundary.

potential benefits of utilizing similar technologies are well known. The United Nations has stated that resource recovery from decentralized wastewater treatment systems has significant potential for producing energy and nutrients for agriculture (UN Water, 2017). Ecological treatment systems have the unique capability of producing both irrigation water (particularly if the effluent of the system is UV disinfected; Sheehan, 2012) and protein-rich plant biomass (ex., duckweed) without requiring the large amounts of energy that are needed to operate conventional treatment systems. Thus, the use of ecological wastewater treatment systems in the developing world has the potential to address multiple societal concerns simultaneously, including wastewater treatment, protein/nutrient production, and access to water for agriculture.

Duckweed, also known as water lentils, are floating aquatic plants from the subfamily Lemnoideae which require only a few millimeters of water depth to grow and can tolerate a large variety of water quality conditions. When grown in nutrient rich environments like wastewater, duckweed grows rapidly and can obtain dry weight protein concentrations of up to 45% (Leng, 1999). Duckweed grown on partially treated wastewater in an Eco-Machine™ was found to produce 5–10 times more protein per area than common land-grown crops, such as oats, soybean, and corn, without accumulating harmful pathogens or metals above the regulatory limits for animal feed (Roman and Brennan, 2019). Despite these benefits, the environmental impacts of producing duckweed on wastewater have not been quantified.

Life cycle assessment (LCA) is a technique to evaluate the environmental impacts of a product or process, considering energy and material inputs, processing or manufacturing, use, disposal, and the emissions and waste that a process or product produces over its lifespan. LCA studies have been conducted on wastewater treatment systems (Dixon et al., 2003; Hospido et al., 2004; Li et al., 2013; and Tabesh et al., 2019) and the production of sustainable protein alternatives, such as insects, seaweed, and algae (Oonincx and de Boer, 2012; Halloran et al., 2016; Gnansounou and Raman, 2016; and van Oirschot et al., 2017). One study analyzed a Living Machine® (similar to an Eco-Machine™) for treating domestic wastewater from an office building, and found that these decentralized systems can reduce total greenhouse gas (GHG) emissions by almost 90% and total energy consumption by 10%, when compared to conventional wastewater treatment systems (Hendrickson et al., 2015). The U.S. EPA estimates that Eco-Machines™ are operationally cost competitive with conventional systems up to flow rates of 1 million gallons (3785 m^3) per day in warm climates, and 600,000 gallons (2270 m^3) per day in cooler climates that require a greenhouse and supplemental heating (United States Environmental Protection Agency, 2002). To date, no LCA studies have been conducted on coupling an ecological wastewater treatment system with protein production.

The aim of the LCA conducted in this study was to identify and quantify the environmental impacts of operating a pilot-scale Eco-Machine™ treating municipal wastewater while concomitantly producing animal feed (derived from duckweed) and irrigation water (derived by UV disinfection of the treated effluent). This is the first LCA to evaluate an ecological wastewater treatment system that produces duckweed and treated wastewater as beneficial outputs of the system. Although this study evaluates one pilot-scale system with a discrete set of products, this analysis is a necessary first step toward understanding where environmental impacts in these systems originate, so that future systems can be designed and operated to maximize environmental sustainability. The results from this study can be used as a basis for developing ecological wastewater treatment systems that are incorporated into domestic animal production operations to facilitate recovering and upcycling of waste nutrients into protein-rich plant biomass. Additional studies would need to be conducted to validate these results for full-scale systems.

2. Methods

2.1. Description of the Penn State Eco-Machine™ and inventory analysis

The model system utilized for this study is a pilot-scale Eco-Machine™ with a capacity of 3785 L day^{-1} that is located at The Pennsylvania State University (University Park, PA, USA) campus. Since this location is within a temperate forest biome that experiences freezing temperatures during part of the year, and the vegetation within the system is mostly tropical, the Penn State Eco-Machine™ is sheltered within a greenhouse which receives supplemental heat via a propane-powered furnace when temperatures drop below 18 °C. A solar power array located outside of the greenhouse, consisting of ten 175 W panels on a tracker system that follows the sun's position throughout the day (Sharp NT-175UC1 panels; Zomeworks UTRF 168 solar tracker), provides nearly 80% of the electricity used within the system. Routine operation of this facility includes weekly delivery of municipal wastewater from the Penn State Wastewater Treatment Plant following rag and grit removal (i.e., primary influent). Wastewater is delivered to an outdoor underground holding tank, from which wastewater is pumped into the greenhouse, where it is treated through a series of six tanks and a subsurface wetland, before passing through a UV disinfection unit. The system is configured as a Modified Ludzack-Ettinger (MLE) process, where the anoxic tanks are located upstream of the aerobic tanks (Fig. 1), and a portion of the nitrate that was converted from ammonia in

Table 1
Inventory used in the life cycle assessment of the Penn State Eco-Machine™ (positive values represent material consumed and negative values represent material produced).

Phase	EcoInvent 3.6 database item	Amount
Construction		
Treatment tanks		
6 HDPE tanks	Polyethylene, high density, granulate, recycled {US}	322.9 kg
1 concrete tank	Concrete, 20 MPa {GLO}	4.5 m^3
Greenhouse		
Block foundation	Concrete block {GLO}	19,320 kg
Glass windows	Flat glass, uncoated {GLO}	1600 kg
Steel beams	Steel, unalloyed {GLO}	1570 kg
Wetland		
Gravel	Gravel, round {GLO}	45,740 kg
Liner	Polyethylene, high density, granulate {GLO}	2596 kg
Piping and valves	Polyvinylchloride, suspension polymerized {GLO}	168.3 kg
Solar panels	Solar glass, low-iron {GLO}	172.4 kg
UV disinfection	Ultraviolet lamp {GLO}	30 p
Operation		
Aeration	Electricity, low voltage {NPCC, US only}	2450 kWh/yr
Pumping	Electricity, low voltage {NPCC, US only}	115.7 kWh/yr
Climate control		
Furnace	Propane {GLO}	2010 kg/yr
Humidifier	Electricity, low voltage {NPCC, US only}	40 kWh/yr
Wastewater delivery	Diesel {GLO}	235 kg/yr
Solar panel	Electricity, low voltage {NPCC, US only}	−2200 kWh/yr
UV disinfection	Electricity, low voltage {NPCC, US only}	36.5 kWh/yr
Products		
Irrigation water	Irrigation {US}	1380 m^3/yr
Duckweed	Tilapia feed, 24–28% protein {GLO}	38.3 kg/yr
Wastewater treatment	Wastewater, unpolluted, from residence {GLO}	−1380 m^3/yr

GLO = global.
US = United States.
NPCC = Northeast Power Coordinating Council.

the aerobic tanks is recycled back to the anoxic tanks for denitrification. A subsurface wetland inside the greenhouse removes the remaining BOD and nutrients. Although natural predation in the Eco-Machine™ has been shown to remove *E.coli* by 70% (Sheehan, 2012), a UV disinfection unit was added to remove remaining bacteria from the system effluent, to ensure they are below the regulatory limits of 126 CFU/100 mL for irrigation water (FDA, 2016).

Duckweed harvested from the Penn State Eco-Machine™ has been tested as a source of protein for animal fodder (Roman and Brennan, 2019), a substrate for bioethanol and biomethane production (Calicioglu et al., 2019), and as a slow-release sustainable soil amendment/fertilizer (Kreider et al., 2019). Of these options, using duckweed as a protein supplement has been calculated to have the highest monetary value on today's markets (Calicioglu, 2019). In this study, the environmental benefits of using the duckweed grown in the Eco-Machine™ as a source of tilapia feed were analyzed, since the need for sustainable aquaculture feed is well established, and duckweed has been previously shown to be an effective supplement for tilapia in various studies (Gaigher et al., 1984; Moreau et al., 1986; and Fasakin et al., 1999). The following water quality parameters were monitored from June 2016 to May 2020 to verify system performance: chemical oxygen demand (Hach Company, Loveland, CO); total nitrogen (Shimadzu TOC-VCSH/CSN analyzer, Columbia, MD); and the anions nitrate, phosphate, and sulfate measured via ion chromatography (Dionex ICS-1100, Sunnyvale, CA) as described previously (Roman and Brennan, 2019). In addition, duckweed within the system was harvested every five days over a period of 5 months, dried, weighed, and tested for crude protein (nitrogen content of the biomass x 6.25; Jones, 1941) to determine protein production. Finally, pathogen counts of *E.coli*, total coliform, and fecal coliform (MacConkey, m-Endo LES, and m FC agar, respectively, Hardy Diagnostics, Springboro, OH) were measured using spread plates in both UV disinfected water and dried duckweed (50 °C for 48 h) to determine if system by-products were below the regulatory limits for irrigation water and agricultural feed.

The LCA of the Penn State Eco-Machine™ inventory was broken into three phases: construction; operation; and products (Table 1). The construction phase consists of six HDPE tanks used for treatment; a concrete underground holding tank; a greenhouse, which includes a block foundation, glass windows, and steel beams; gravel and HDPE liner for the wetland; piping and valves; solar panels; and a UV disinfection unit. The operation phase consists of: electricity used for aeration, pumping, air humidification, and UV disinfection; and propane used to heat the greenhouse in the winter months. Products include irrigation water (UV disinfected treated wastewater); duckweed used for tilapia feed; and treated wastewater. The functional unit of the analysis is million liters (ML) wastewater treated.

2.2. *Duckweed characteristics*

Duckweed grown in the Penn State Eco-Machine™ was previously reported to have an average growth rate of 7 g m^{-2} day^{-1} and a protein content of 38% (Roman and Brennan, 2019). For the LCA, a growth area of 44.5 m^2 (the size of the wetland in the Penn State Eco-Machine™) was assumed available to grow duckweed year-round. There is no database item for duckweed within EcoInvent, so a common product that duckweed can replace was used as a proxy: tilapia feed (24–28% protein; GLO). Duckweed has been shown to be an effective replacement for conventional fishmeal in the diet of tilapia (Gaigher et al., 1984; Fasakin et al., 1999). In fact, some studies have shown that duckweed can be used as the sole component of the diet without sacrificing the survival rate of the fish (Hassan and Edward, 1991). As a conservative estimate, a 30% replacement of conventional tilapia fishmeal with duckweed was used for this study, which has been shown to be the most cost effective diet in terms of cost per unit weight gain of fish (Fasakin et al., 1999). Thus, the duckweed produced in the Eco-Machine™ was assumed to offset 30% of the detrimental impacts associated with producing tilapia feed on a mass basis (which includes impacts to agriculture, animal husbandry, fisheries, energy expenditures (electricity and industrial heat), and direct emissions to aquatic environments). It was also assumed that aquaculture operations would be co-located with the Eco-Machine™; therefore, downstream duckweed processing such as packaging and transportation were not included in this analysis. The resulting impacts could reasonably be expected to differ from the actual impacts associated with duckweed utilization; therefore this LCA could be improved in the future with a more refined database item for duckweed.

2.3. *Life cycle impact assessment (LCIA)*

SimaPro 9.0 was used for the life cycle inventory analysis and impact assessment calculations, coupled with the EcoInvent 3.6 database (system model = allocation, cut-off by classification; process data = unit) and no amendments were made to the datasets other than the proxy of duckweed as tilapia feed. Impact 2002+ was used as the methodology for the impact assessment due to its reliability for both agricultural processes and environmental treatment LCAs (Jolliet et al., 2003), which are uniquely combined in this study. The method quantifies four damage categories: human health; ecosystem quality; climate change; and resources. Within these damage categories, 15 midpoint categories were quantified: carcinogens; non-carcinogens; respiratory inorganics; ionizing radiation; ozone layer depletion; respiratory organics; aquatic ecotoxicity; terrestrial ecotoxicity; terrestrial acidification/nutrification; land occupation; aquatic acidification; aquatic eutrophication; global warming; non-renewable energy; and mineral

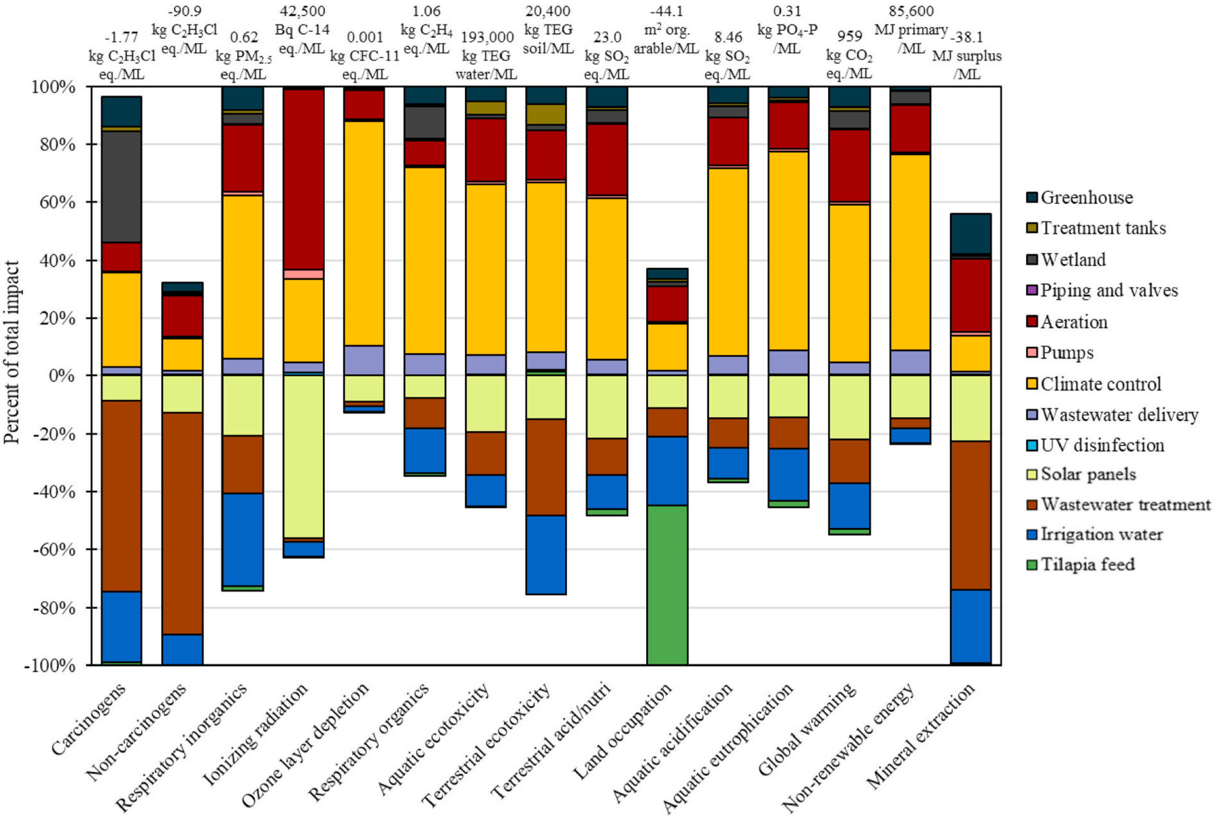

Fig. 2. Midpoint category impacts of the Penn State Eco-Machine™. Net impact value per million liter (ML) treated for each category is listed above (positive values represent detrimental impacts and negative values represent beneficial impacts).

extraction (Humbert et al., 2012).

The human health damage category is the sum of the following midpoint categories: carcinogens; non-carcinogens; respiratory inorganics; ionizing radiation; ozone layer depletion; and respiratory organics. Human health impacts are expressed in "Disability-Adjusted Life Years" (DALY), which characterizes disease severity, accounting for both mortality and morbidity. Human health is dominated by respiratory effects caused by inorganic substances emitted into the air (Humbert et al., 2012).

The ecosystem quality damage category is the sum of the midpoint categories: aquatic ecotoxicity; terrestrial ecotoxicity; terrestrial acidification/nutrification; land occupation; aquatic acidification; and aquatic eutrophication. Ecosystem quality impacts are expressed in "Potentially Disappeared Fraction of species over a certain amount of m^2 during a certain amount of year" (PDF-m^2-yr). Ecosystem quality is dominated by terrestrial ecotoxicity and land occupation (Humbert et al., 2012).

The climate change damage category includes one midpoint category: global warming. Climate change impacts are expressed in kg $CO_{2\text{-eq}}$ and are dominated by greenhouse gas emissions (Humbert et al., 2012).

The resources damage category is the sum of non-renewable energy and mineral extraction midpoint categories. Resources impacts are expressed in Megajoules (MJ) and is largely dominated by non-renewable energy consumption (Humbert et al., 2012).

2.4. Sensitivity analysis

A Monte-Carlo analysis was performed within SimaPro to determine the uncertainty in the inventory data for the damage categories (95% CI). A sensitivity analysis was performed to determine how a greenhouse and heating affect the overall impacts of the system. Additionally, using vertical farming techniques to increase the duckweed growth area and yield was investigated.

3. Results and discussion

3.1. Midpoint categories

The midpoint impact characterization for the individual components of the Penn State Eco-Machine™ are shown in Fig. 2. The detrimental impacts (positive values) outweighed the beneficial impacts (negative values) in the majority of midpoint categories, except carcinogens, non-carcinogens, land occupation, and mineral extraction.

3.1.1. Detrimental impacts

As the pilot system in this study is currently operated, including a greenhouse and supplemental heating, the major detrimental impacts are from climate control, aeration, and construction of the greenhouse/wetland. Some of these impacts, however, could be mitigated with changes in design or operation.

Climate control is responsible for the largest detrimental impact for 10 midpoint categories: respiratory inorganics (56.5%); ozone layer depletion (77.8%); respiratory organics (64.7%); aquatic ecotoxicity (59.0%); terrestrial ecotoxicity (58.7%); terrestrial acidification/nutrification (55.6%); aquatic acidification (64.8%); aquatic eutrophication (68.7%); global warming (54.6%); and non-renewable energy (67.5%). Climate control in the Penn State Eco-Machine™ is provided by a propane furnace and a humidifier; there is no air conditioning. Propane used to heat the greenhouse is responsible for nearly all of the detrimental impacts from climate control. The Eco-Machine™ had an average propane usage of 1077 gallons per year (based on data collected from 2018 to 2020). Operating Eco-Machines™ (and other indoor ecological wastewater treatment systems) in climates with moderate

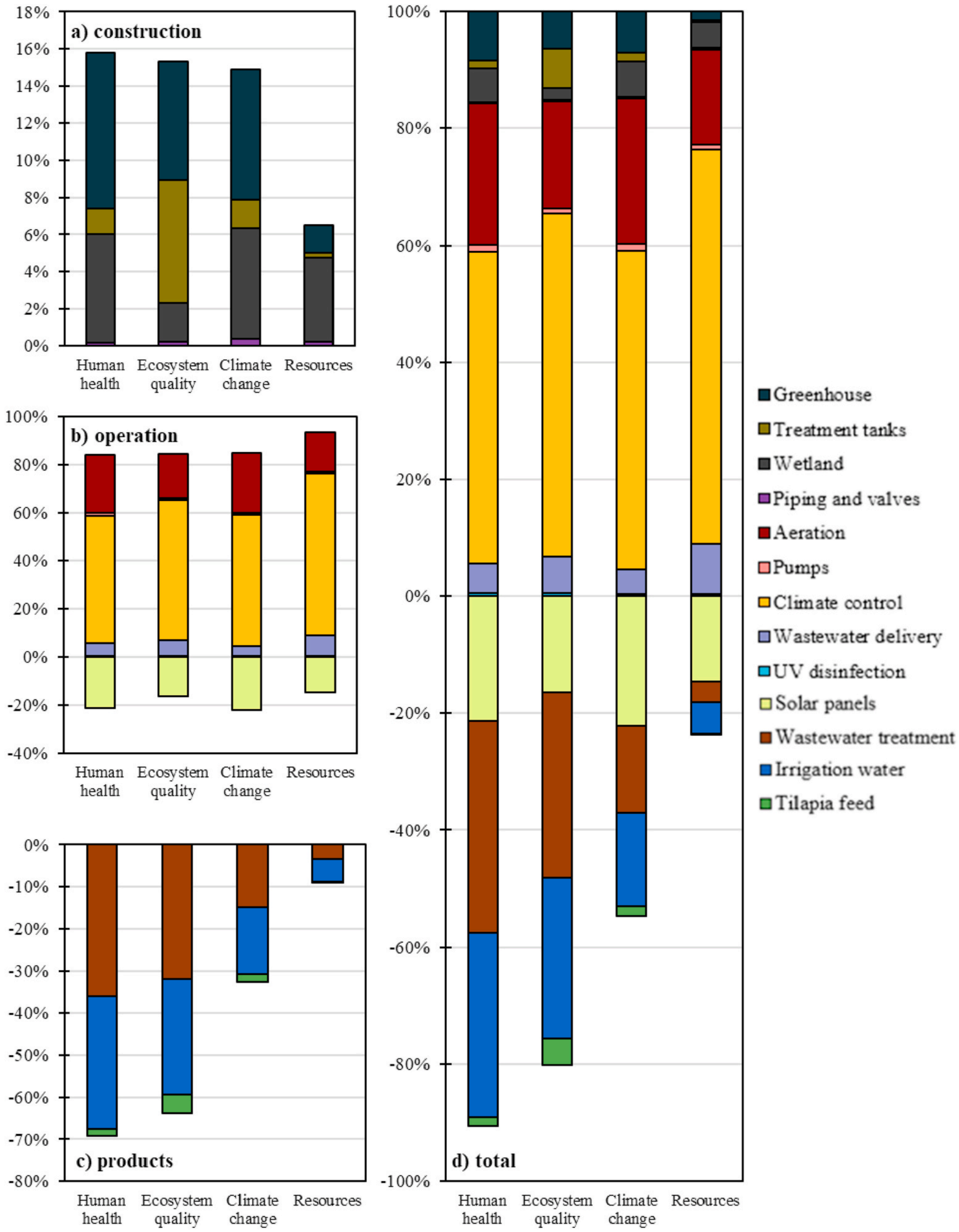

Fig. 3. Damage assessment of three phases of the Penn State Eco-Machine™: a) construction; b) operation; c) products; and d) total (see Table 1 for inventory; positive values represent detrimental impacts and negative values represent beneficial impacts).

temperatures year-round would remove the need for heating, and greatly reduce the detrimental impacts.

Aeration is responsible for the largest detrimental impact for three midpoint categories: non-carcinogens (14.1%); ionizing radiation (62.5%); and mineral extraction (25.5%). Aeration is provided to the aerobic tanks by two air compressors that each operate for 6 h per day, consuming nearly 2500 kWh of electricity per year. This result is consistent with conventional wastewater treatment systems, where aeration typically accounts for over 75% of the total energy used (Cantwell et al., 2017). Strategies for reducing the energy cost for aeration in Eco-Machines™ include: installing fine-bubble diffusers and reducing fouling; installing mechanical mixers in the aerobic tanks to increase oxygen use efficiency; and adding a trickling system that allows the wastewater to pass over shallow steps to naturally aerate between tanks.

The construction of the greenhouse and wetland is responsible for the largest detrimental impact for the final midpoint category: carcinogens (38.5%). This study assumed that raw materials were used to build the greenhouse/wetland; however, recycled/reclaimed materials could be at least partially used to construct such systems (ex., recycled concrete blocks for the foundation, recycled gravel for the wetland, etc.). In addition, a greenhouse would not be necessary if the system were located in a tropical/equatorial region, which would greatly reduce construction impacts.

Although not a leading detrimental impact in any category, wastewater delivery is responsible for >5% of the total impact in most midpoint categories. Currently, a 2000 gallon (7.6 m^3) tanker truck is used to transport primary influent wastewater one mile (1.6 km) from the wastewater treatment plant to the Eco-Machine™. Ideally, wastewater would be piped directly to the Eco-Machine™, but shallow bedrock on the site prohibited the construction of underground sewage pipes. In practice, an Eco-Machine™ should be connected directly to the

Table 2
Damage assessment results of the three phases of the Penn State Eco-Machine™ per million liters (ML) treated. The Monte-Carlo analysis standard deviation is shown for each phase at each damage category (95% CI; positive values represent detrimental impacts and negative values represent beneficial impacts).

Damage category	Construction	Operation	Products	Total
Human health (DALY/ML)	$3.1E^{-4}$ $\pm 2.4E^{-5}$	$1.2E^{-3}$ $\pm 2.2E^{-4}$	-1.4^{-3} $\pm 2.9E^{-4}$	**$1.7E^{-4} \pm$ $3.9E^{-4}$**
Ecosystem quality (PDF-m^2-yr/ML)	110 ± 20	500 ± 370	−470 ± 64	**170 ± 480**
Climate Change (kg CO_2 eq./ML)	320 ± 14	1300 ± 90	−690 ± 70	**960 ± 110**
Resources (MJ/ML)	7300 ± 220	87,000 ± 14,000	−10,000 ± 1000	**86,000 ± 14,000**

sewage pipes to avoid having to transport wastewater to the system by truck.

The remaining detrimental impacts stem from the treatment tanks, piping and valves, pumps, and UV disinfection, which collectively account for less than 5% of the total impacts for all but two midpoint categories: aquatic ecotoxicity (5.8%); and terrestrial ecotoxicity (8.6%).

3.1.2. *Beneficial impacts*

The beneficial impacts from the Eco-Machine™ in this study result from the renewable electricity produced by the solar panels, wastewater treatment, irrigation water (treated wastewater), and tilapia feed (duckweed) produced within the system.

The integrated solar array is responsible for the largest beneficial impact for seven midpoint categories: ionizing radiation (−56.1%); ozone layer depletion (−9.0%); aquatic ecotoxicity (−19.4%); terrestrial acid/nutri (−21.7%); aquatic acidification (−14.7%); global warming (−22.1%); and non-renewable energy (−14.6%). The solar array provides roughly 80% of the total electricity used by the Eco-Machine™ annually, however, during the summer months, the solar panels provide more electricity than the Eco-Machine™ consumes, and the additional electricity is sent to the university grid. Since this relatively small solar panel system provides the majority of the electricity needed throughout the year, it suggests that Eco-Machines™ could be easily designed to operate with only electricity produced by a larger solar array, greatly reducing their long-term detrimental impacts.

Wastewater treatment is responsible for the largest beneficial impact for four midpoint categories: carcinogens (−65.8%); non-carcinogens (−76.7%); terrestrial ecotoxicity (−33.3%); and mineral extraction (−51.5%). This study assumes that if not treated by the Eco-Machine™, the wastewater would otherwise remain untreated to fairly compare this system to other wastewater treatment systems. From a global perspective, this is realistic, as approximately 80% of the world's wastewater is discharged without treatment into the environment (NRDC, 2018). Ecological wastewater treatment systems are ideal for addressing this problem, especially in developing regions, since they require little energy and infrastructure to operate.

Irrigation water produced by the Eco-Machine™ is responsible for the largest beneficial impact for three midpoint categories: respiratory inorganics (−32.2%); respiratory organics (−15.4%); aquatic eutrophication (−17.9%).

Tilapia feed is responsible for the largest beneficial impact for one midpoint category: land occupation (−55.1%).

3.2. *Damage categories*

The damage category impacts (human health, ecosystem quality, climate change, and resources) caused by the Penn State Eco-Machine™ were grouped into three phases to facilitate the analysis and discussion that follows: construction (Fig. 3a), operation (Fig. 3b), and products (Fig. 3c).

3.2.1. *Human health*

The net impact to human health from the Penn State Eco-Machine™ is 1.69 E^{-4} ± 3.86 E^{-4} DALY/million liters (ML) treated wastewater (Table 2). The near zero value indicates that the system has little to no detrimental impacts on human health. Although minimal, the largest of the detrimental impacts to human health are caused by climate control (53.5%), followed by aeration (24.1%), and greenhouse construction (8.4%). The largest beneficial impacts to human health are from wastewater treatment (−36.2%), irrigation (−31.5%), and the solar panels (−21.4%).

For the Eco-Machine™, the propane consumed, and thus the detrimental impacts from natural gas processing and oil refining, is the largest contributor to detrimental human health effects. Electricity consumption, and thus the emissions from the power plants producing the electricity, is the other largest contributor to the detrimental human health effects. However, since the solar array produces about 80% of the total electricity consumed by the system, the detrimental human health impacts from producing electricity in a power plant are largely offset. Additionally, the energy required to treat wastewater in a conventional plant is not needed if wastewater is treated in the Eco-Machine™, creating a beneficial impact to human health. Lastly, utilizing the irrigation water produced by the Eco-Machine™ on nearby farmland removes the detrimental impacts of the infrastructure and energy needed to pump water from a surface/ground water source for irrigation.

3.2.2. *Ecosystem quality*

The net impact to ecosystem quality from the Penn State Eco-Machine™ is 170 ± 480 PDF-m^2-yr/ML (Table 2). The largest detrimental impacts to ecosystem quality are from climate control (58.7%), aeration (18.4%), and treatment tanks (6.6%). Similar to human health, the largest beneficial impacts to ecosystem quality are from wastewater treatment (−31.8%), irrigation water (−27.6%), and the solar panels (−16.4%).

3.2.3. *Climate change*

The net impact to climate change from the Penn State Eco-Machine™ is 958 ± 114 kg $CO_{2\text{-eq}}$/ML (Table 2). The largest detrimental impacts to climate change are from climate control (54.6%), aeration (24.9%), and greenhouse construction (7.0%). The largest beneficial impacts to climate change are from solar panels (−22.1%), irrigation (−15.9%), and wastewater treatment (−14.9%). This analysis likely underestimates the beneficial impacts to climate change from the Eco-Machine™, as photosynthesis by plants in the system was neglected. For example, Taro (*Colocasia esculenta*) grows in the aerobic tanks, and is known to sequester carbon at a rate of 10.4 ± 5.2 g C/m^2-day (Saunders et al., 2012). Given an estimated surface area of 2.33 m^2 for Taro in the Eco-Machine™, it could theoretically sequester ~24 g C/day, or 8.8 kg C/year, which would offset approximately 0.7% of the total CO_2 emissions from operating the Eco-Machine™ for one year (Belles, 2020). If C sequestration from all the plants in the Eco-Machine™ were included, it would likely reduce the CO_2 emissions from the system by less than 5% (Belles, 2020). Frequent harvesting of duckweed in a vertical farming system would likely increase C uptake, however, so beneficial impacts to climate change in that scenario would require further investigation.

Consistent with human health and ecosystem quality, over half of the detrimental impacts on climate change are from the oil refining and processing required to create the propane which is burned to heat the greenhouse in the winter. Replacing propane with natural gas would reduce the detrimental impacts in the climate change category by nearly 70%.

Although operating the Eco-Machine™ in a temperate zone with a propane furnace results in net detrimental impacts to climate change, it is still only about a third of the climate change impacts produced by the operation of a conventional wastewater treatment (3000 kg $CO_{2\text{-eq}}$/ML; Hendrickson et al., 2015). It should be noted that environmental impacts

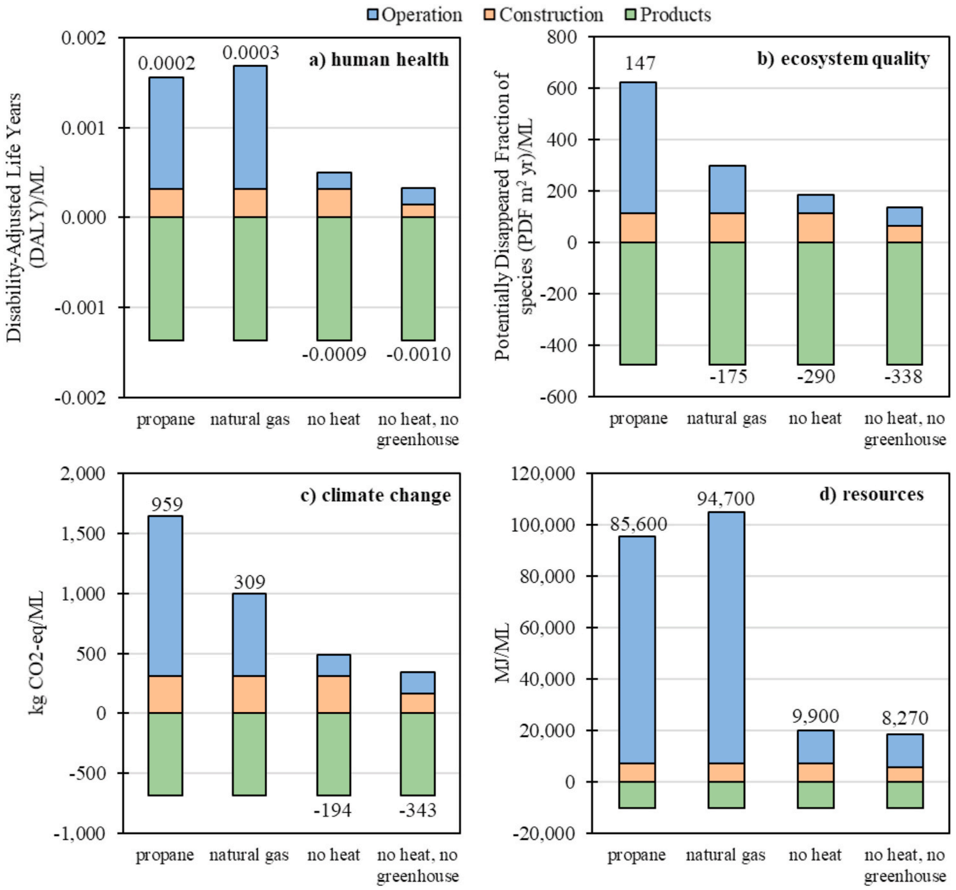

Fig. 4. Impacts of the Eco-Machine™ with propane heating, natural gas heating, no heating, and no heating and no greenhouse per million liters (ML) wastewater treated at the four damage categories: a) human health; b) ecosystem quality; c) climate change; and d) resources. Net impact is shown adjacent to the bar in each plot (positive values represent detrimental impacts and negative values represent beneficial impacts).

from the release of GHGs from microbial metabolic processes during wastewater treatment (i.e., carbon dioxide, methane, nitrous oxides) were not considered in this LCA of the Eco-Machine™, and therefore it likely underestimates the total GHG emissions from the system.

3.2.4. Resources

The net impact to resources from the Penn State Eco-Machine™ is 85,700 ± 13,900 MJ/ML (23,800 kWh/ML; Table 2). Climate control (67.5%) is responsible for over half of the detrimental impact, followed by aeration (16.3%), and wastewater delivery (8.6%). The solar array (−14.6%) provides the largest beneficial impact to resources, followed by irrigation water (−5.4%), and wastewater treatment (−3.5%).

As currently operated, the detrimental impact to resources from the Penn State Eco-Machine™ (23,800 kWh/ML) is 4–5 times higher than the impact to resources from conventional wastewater treatment (~5000 kWh/ML; Hendrickson et al., 2015). This is for two reasons: 1) the furnace used to heat the greenhouse in the winter currently consumes propane; and 2) biogas produced during conventional treatment is typically recovered and used to heat various treatment processes throughout the treatment plant (Noyola et al., 2005). In its current configuration, the Penn State Eco-Machine™ does not produce a significant quantity of biogas as it does not contain an anaerobic digester. Methane is below detection in the tanks, so it is likely that any methane production occurring deep within the tanks is likely consumed by methanotrophic organisms in the upper water layers that are exposed to oxygen through diffusion. For methane capture to be possible, either an anaerobic digester would need to be added to the system, or the anaerobic tanks would need to be redesigned to avoid aerobic zones in the upper layers.

When the need for heating the greenhouse with propane is removed, the impact to resources from the Eco-Machine™ is reduced to 2750 kWh/ML, or about half of the impacts from conventional wastewater treatment.

3.3. Sensitivity analysis on heating/greenhouse requirements

Based on the results of the damage assessment of the Penn State Eco-Machine™, it is obvious that removing the need for housing the system within a heated greenhouse would greatly reduce its detrimental impacts. A comparison of the impacts from four scenarios are shown in Fig. 4: propane heated greenhouse, natural gas heated greenhouse, non-heated greenhouse, and no heat and no greenhouse. The largest reduction in detrimental impacts comes from the need to heat the greenhouse, which transforms the Eco-Machine™ from producing detrimental impacts at all four damage categories to producing a beneficial impact (negative value) in the human health, ecosystem quality, and climate change damage categories (Fig. 4). Changing from propane to natural gas heating reduces the detrimental impacts for ecosystem quality and climate change, but increases the detrimental impacts for human health and resources. IMPACT 2002+ offers a 'weighted' single score impact, that accounts for the overall importance of each damage category and weights them accordingly, allowing for the four damage categories to be compared with the same units. When the Eco-Machine™ heated with propane versus natural gas are compared with weighting, propane heating produces 1.4% more total detrimental impacts than natural gas, indicating that natural gas heating would slightly improve the overall sustainability of the Penn State Eco-Machine™. This result indicates that Eco-Machines™ are capable of producing net benefits to all damage

Table 3
Duckweed vertical growth tray inventory data used in the sensitivity analysis.

IMPACT 2002+ database item	Amount			
	1 stack	*2 stacks*	*3 stacks*	*4 stacks*
Steel, unalloyed {GLO}	170 kg	240 kg	310 kg	380 kg
Polyethylene, high density, granulate, recycled {US}	0.863 kg	1.726 kg	2.589 kg	3.452 kg
Plywood, for indoor use {RoW}	0.565 m^3	1.13 kg	1.695 kg	2.26 kg
Electricity, low voltage {NPCC, US only}	–	1117 kWh	2234 kWh	3351 kWh
Tilapia feed, 24–28% protein {GLO}	1150 kg	2300 kg	3450 kg	4600 kg

GLO = global.
US = United States.
NPCC = Northeast Power Coordinating Council.

categories expect resources, when located in areas that do not require heating.

3.4. Sensitivity analysis on vertical farming options to increase duckweed growth area

One of the benefits of duckweed is that it only requires a few millimeters of water depth to grow, making it well suited for vertical farming (Leng, 1999). Therefore, a sensitivity analysis was performed to examine the potential beneficial impacts of utilizing multiple stacks (1–4) of duckweed growth platforms covering the area of the wetland (44.5 m^2) to increase the duckweed growth area in the Penn State Eco-Machine™. A steel frame was used to support the vertical duckweed growth trays, which were assumed to be made of plywood sheets lined with an HDPE liner, which is a common configuration for hydroponic systems. LED light strips installed underneath the trays provide light to the duckweed growing in the tray beneath. No LED lights were used above the top tray or in the single stack scenario, since sunlight would not be impeded by another tray above. The inventory used for the vertical growth sensitivity analysis is presented in Table 3.

Increasing the number of vertical stacks used to grow duckweed provides additional beneficial impacts for human health (Fig. 5a), ecosystem quality (Fig. 5b), and climate change (Fig. 5c), but increases detrimental impacts for resources (Fig. 5d). The majority of the detrimental impact in the resource category was due to the electricity used to power the LED grow lights. In each damage category aside from resources, the plywood used as the base of the growth platform provided the largest detrimental impact, suggesting that the use of recycled wood or another recycled container system could eliminate a substantial portion of the detrimental impacts of the vertical farming system. Nonetheless, the results suggest that the additional beneficial impacts from producing more duckweed outweigh the detrimental impacts from constructing vertical farming system and the energy required to power the LED lights (Fig. 6).

4. Conclusions

A life cycle assessment conducted on a pilot-scale Eco-Machine™ showed that the detrimental impacts from these systems are dominated by the fuel source used to heat the greenhouse and aeration. It was

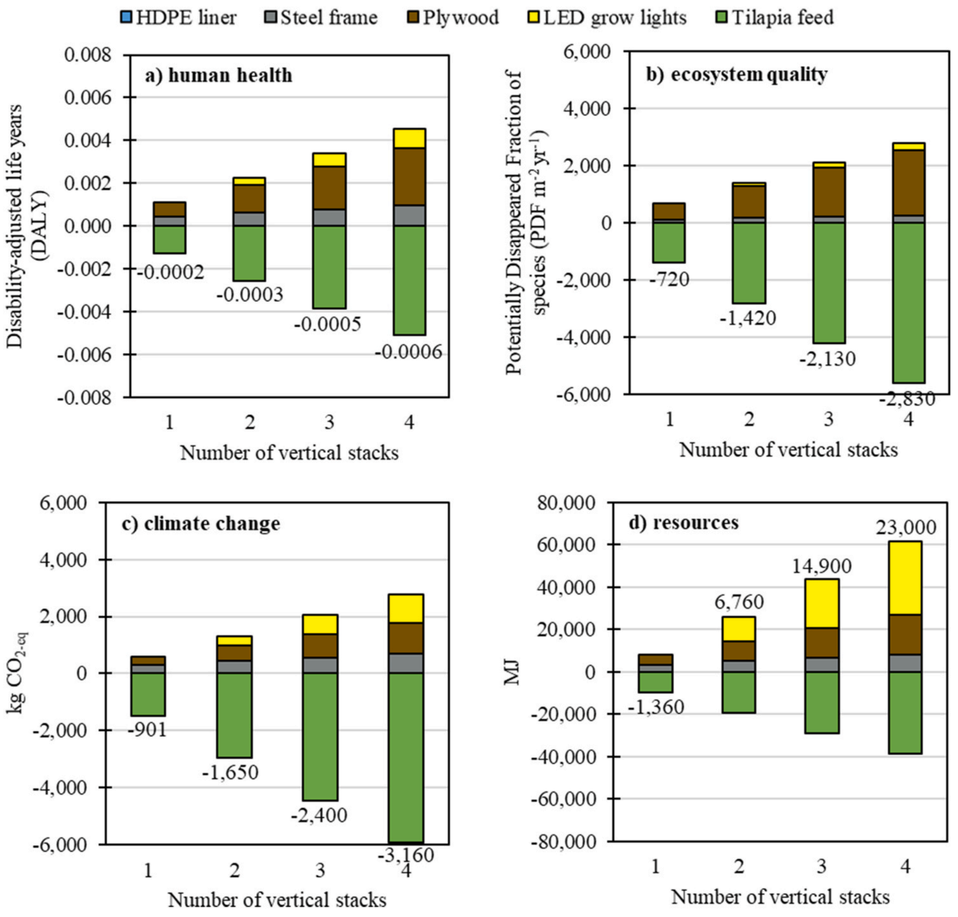

Fig. 5. Vertical farming sensitivity analysis on the impact of the number of vertical trays for duckweed growth in each of the four damage categories: a) human health; b) ecosystem quality; c) climate change; and d) resources. The net impact for each damage category are shown adjacent to the bars (positive values represent detrimental impacts and negative values represent beneficial impacts).

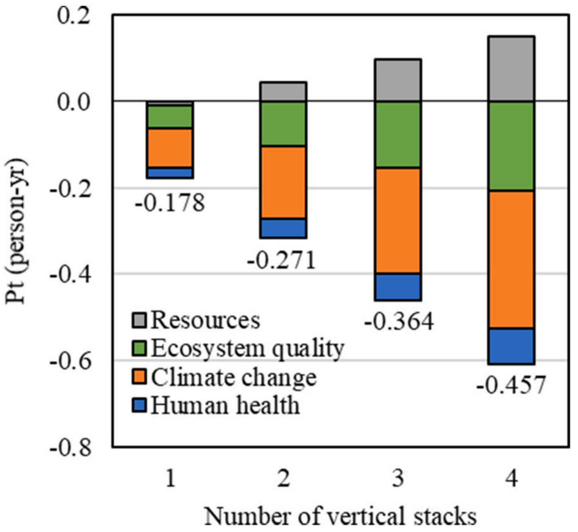

Fig. 6. Vertical farming weighted impacts of damage categories based on the number of vertical trays used for duckweed growth. Positive values represent detrimental impacts and negative values represent beneficial impacts.

determined that if the greenhouse were located in a region that does not require heating, the system would transform detrimental impacts for human health, ecosystem quality, and climate change into beneficial impacts. Fine bubble diffusers, mechanical mixers, or a passive trickling system incorporated into the Eco-Machine™ could reduce the detrimental impacts from aeration. The integrated solar array provides the largest beneficial impact to the system by producing nearly 80% of the electricity that the Eco-Machine™ consumes. Currently, the solar array only consists of ten solar panels, and could be easily expanded to produce all of the energy needs of the Eco-Machine™. As currently operated, the Penn State Eco-Machine™ produces about a third of the CO_2 emissions as conventional wastewater treatment systems. The impact of the Penn State Eco-Machine™ to resources is about 4–5 times higher than conventional wastewater treatment; however, if the need for heating were removed, it would produce about one-half of the impacts to resources as conventional wastewater treatment. Finally, providing additional area for duckweed growth in the form of a vertical farming system increases the overall sustainability of the system by producing more protein-rich plant biomass. The results from this study do not consider the potential environmental impacts from microbial metabolic processes (i.e., carbon dioxide, methane, nitrous oxides) occurring within the Eco-Machine™. Future research should investigate how these types of systems scale with treatment capacity, and validate the safety of duckweed biomass generated from different wastewater sources for use as animal feed. In addition, LCAs of ecological treatment systems coupled with duckweed growth for use in other products (ex., fertilizer, bioenergy) should be conducted to quantify the impact of using these systems for meeting various community needs.

Credit author statement

Roman, B: Methodology; Investigation; Data curation; Software; Formal analysis; Visualization; Writing – original draft. Brennan, R.A: Supervision; Project administration; Funding acquisition; Writing – review & editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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