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Sustainable Production of Fertilizers via Photosynthetic Recovery of Nutrients in Livestock Waste

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ABSTRACT

Increases in population and improvements in living standards have significantly increased the demand for animal products worldwide. However, modern livestock agriculture exerts significant pressure on the environment due to high material and energy requirements. These systems also generate significant amounts of waste that can cause severe environmental damage when not handled properly. Thus, if we wish to enable farmers to meet this increased demand in a sustainable way, technology pathways must be developed to convert livestock agriculture into a more circular economy. With this end in mind, we propose a novel framework (which we call ReNuAl) for the recovery of nutrients from livestock waste. ReNuAl integrates existing technologies with a novel biotechnology approach that uses cyanobacteria (CB) as a multi-functional component for nutrient capture and balancing, purifying biogas, and capturing carbon. The CB can be applied to crops, reducing the need for synthetic fertilizers like diammonium phosphate. Using manure profiles obtained from dairy farms in the Upper Yahara region of Wisconsin, we construct a case study to analyze the environmental and economic impacts of ReNuAl. Our results illustrate that the minimum selling price (MSP) of CB fertilizer produced from deploying ReNuAl at a 1000 animal unit (AU) farm is significantly higher than the cost of synthetic fertilizers. We also observe that ReNuAl can return environmental benefits in areas such as climate change and nutrient runoff when compared to current practices. As a result, we see that consideration of environmental incentives can significantly increase the economic viability of the process.

Keywords: Process Design, Technoeconomic Analysis, Life Cycle Analysis

INTRODUCTION

The UN Food and Agriculture Organization projects that demand for animal products will increase by up to 70% by 2050 [1]. This represents an opportunity for significant economic growth for areas that specialize in livestock agriculture like the Upper Yahara region of Wisconsin. However, meeting this demand also presents a significant sustainability challenge. Livestock agriculture is a resource-intensive venture: production of 1 kg of fat and protein corrected milk requires 2.7 MJ of energy, 2.61 kg of nitrogen (N), and 0.4 kg of phosphorus (P) [2, 3]. While nitrogen is a renewable resource, phosphorus and the required energy are usually sourced from non-renewable feedstocks [4]. Concurrently, these systems generate large amounts of waste, mostly in the form of animal manure [5]. The most common method for managing this waste is to apply it to cropland where it can serve as a fertilizer. However, this approach leads to several undesirable environmental outcomes. Manure breaks down when exposed to sunlight and releases potent greenhouse gases (GHGs) like N_2O and CH_4; this practice has been measured to have a global warming potential (GWP) of 72.5 kg CO_2-eq/tonne of manure. Additionally, because livestock waste has a low N:P ratio, it is often overapplied to meet crop N requirements; this results in the overloading of soils with P [6]. This, in turn, leads to excess nutrients being washed out into surrounding waterways where they cause harmful algal blooms (HABs). In addition to severe environmental damage to aquatic ecosystems, these eutrophication events also result in significant health and economic damage to the residents of neighboring communities [7].

Technologies that provide alternative methods for handling livestock manure have existed for decades. The use of anaerobic digesters (ADs), which were developed in the early 20th century, in a farm setting was initially considered during the 1970s in response to an energy crisis [8]. ADs use microorganisms that feed on raw manure to generate a gas mixture, commonly referred to as biogas, largely composed of CO_2 and CH_4 that can serve as a renewable energy source. Additionally, by breaking down manure in a more controlled setting, ADs are able to prevent the release of GHG emissions seen in land application. However, the leftover material, known as digestate, has a similar N:P ratio as manure, and also leads to nutrient overloading when applied to cropland. Water recovery systems (WRS) offer a solution to this issue by providing further separation capabilities for the digestate. The central aim of a WRS is to recover clean water from manure. This is achieved using a solids-liquids separator (SLS) followed by ultrafiltration (UF) and reverse osmosis (RO) systems [9]. This allows for the separation of P and N nutrients. The solid product contains most of the P while the N is largely recovered in a concentrated solution following the UF and RO steps [10]. While this allows for variable nutrient loading, additional infrastructure and management protocols are required to ensure that these products are properly stored and applied [9].

Cyanobacteria (CB) are aquatic photosynthetic bacteria with high productivity compared to terrestrial plants [11, 12] that have been shown to be capable of processing nutrient-rich streams like manure or digestate [13, 14]. In fact, HABs are the result of the rapid growth of certain species of CB in nutrient-rich water. We propose harnessing this ability in a more controlled way to cultivate this organism for use as a biofertilizer. In addition to recycling nutrients and reducing nutrient leaching, CB fertilizer has been shown to improve soil health, reduce erosion, and has a smaller carbon footprint when compared to synthetic fertilizers [15-17]. To this end, we present the Renewable Nutrients from Algae (ReNuAl) process, a small and low-intensity operation for the production of CB fertilizer from manure. This technology pathway is centered around the use of CB strains that are engineered to have N and P content ratios that match crop nutrient requirements. We study the economic metrics of this process using a technoeconomic (TEA) model of ReNuAl at a hypothetical 1000 animal unit (AU) diary farm in the Upper Yahara. The calculated minimum selling price (MSP) of the biofertilizer, while similar to the value reported in another study [18], is significantly higher than the cost of synthetic fertilizers. However, a preliminary life cycle assessment (LCA) of the process indicates that ReNuAl has the potential to deliver substantial environmental benefits when compared to direct land application. Thus, the consideration of environmental incentives can reduce the fertilizer MSP significantly.

COMPUTATIONAL FRAMEWORK

In this section we present the ReNuAl process, state the assumptions made in the process models, and provide a description of the proposed computational framework. As seen in Figure 1, the front end of ReNuAl pairs anaerobic digestion with CB cultivation and harvesting. This integration allows for the continued recovery of energy from manure via biogas in tandem with biofertilizer production, providing the process with multiples product streams. The CB are cultivated in bag photobioreactors (b-PBRs), and their growth is assumed to be light-limited. We assume that two thirds of the produced biogas is exported to the grid while the remaining third is burned for on-site power generation. The flue gas is scrubbed, and the CO_2 is fed to the cyanobacteria. Solids in the digestate are removed in a solids-liquids separation unit, and the liquid fraction is pumped into the b-PBRs along with any additional N required in the form of urea. Once the CB are ready to be harvested, they are sent to a dewatering train consisting of a flocculation tank, clarifier, and pressure filter that yields a concentrated CB solution. This stream is then fed to a thermal dryer to achieve the desired moisture level. CB growth in the b-PBRs is simulated using a detailed growth model based on the work of Straka [22] while the remaining units are simulated with linearized models using yield factors found in the literature. The ReNuAl process is fed 11.7 tonnes/yr of N and 10.6 tonnes/yr of P from 20800 tonnes/yr of manure. The b-PBRs receive 350 μmol/m^2·s of sunlight and are harvested every 30 days. The P content of the CB is assumed to be 0.023 g P/g CB resulting in a production rate of 419 tonnes/yr of fertilizer. Using these unit operations models and system parameters, we calculate the mass and energy flows of the process and the required size of the process units. This information is then used to determine the capital investment as well the yearly operating costs and revenues of ReNuAl. Note that prices are set in terms of 2020 USD and the process is assumed to have a lifetime of 20 years.

The MSP is calculated by determining the price at which the fertilizer must be sold to achieve a discounted return on investment (DROI) of 15%. The DROI is defined as the discount rate that results in a net present value (NPV) of 0 at the end of the project life where:

$$NPV = C + \sum_{t=1}^{T} P(1+i)^{-t} \quad (1)$$

The DROI is denoted by i, T is the project lifetime (in years), C is total capital investment (TCI) and P is the annual after-tax profit (AATP) and is formulated as:

$$P = (1-r)\left(p_f \dot{m}_f + p_g \dot{m}_g + p_e \dot{w} - p_o - d\right) + d \quad (2)$$

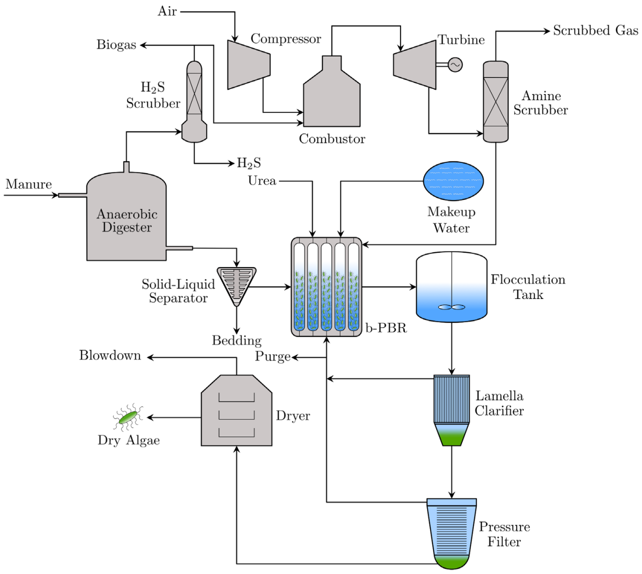

Figure 1. ReNuAl process configuration

where the production rates of fertilizer, biogas and electricity are represented by $\dot{m}_f$, $\dot{m}_g$, and $\dot{w}$ respectively and these are sold at p_f, p_g, and p_w. The term r is the tax rate, p_o is the total annual operating cost (TOC), and d is the annual depreciation of the process equipment. Note that the values in (2) are held constant throughout the lifetime of the project. Thus, the MSP is defined as the value of p_f that results in a value 0 for (1) when $i = 0.15$.

We use the material and energy flows calculated by the process model to develop a preliminary LCA to quantify the environmental benefits of ReNuAl over current practices. The LCA is performed using openLCA in conjunction with the Environmental Footprint and AGRIBALYSE databases and the Environmental Footprint impact assessment method [19, 20, 21]. The functional unit is set to be the size of the dairy farm (1000 AU), and we consider that the electricity demands are satisfied using the average electricity mix in the US. The impact categories considered in this study are climate change and water use. We valorize the observed benefits using existing frameworks, such as RIN and LCFS credits and a hypothetical P credit based on the economic impact of P runoff as quantified in [7], in order determine the effect of these additional cash flows on the product MSP.

RESULTS AND DISCUSSION

We determined that the construction and operation of the ReNuAl process have a cost of 4.36 MMUSD and 2.73 MMUSD/yr respectively. At these values, the fertilizer would have to be sold for 7.75 USD/kg to meet the DROI target. This is significantly higher than the 0.25 USD/kg that it would cost to obtain the equivalent N and P content using synthetic fertilizers.

From Figure 2, we can see that TCI and TOC are not evenly distributed across the various sections of the process. The anaerobic digester and thermal dryer alone account for over 60% of the TCI while the operation of the b-PBRs represents about 75% of the TOC. This indicates that by exploring alternative process configurations or extending the capabilities of the CB, we might be able to significantly decrease these costs and, by extension, the MSP. For example, a CB strain that can clean the biogas by removing H_2S and CO_2 can reduce the capital cost by 11% by eliminating the need for gas scrubbers. Similarly, if it is not necessary to completely dry the CB or if strains that are more easily recoverable via sedimentation and filtration are used, then it might be possible to reduce the size of the thermal dryer or eliminate it completely.

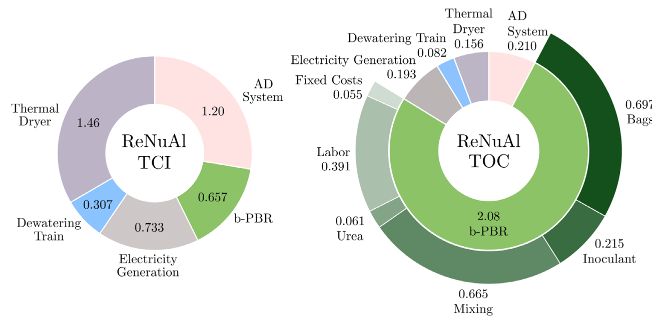

Figure 2. Distribution of total capital (left) and operating (right) costs in MMUSD across the sections of the ReNuAl process

While the economic metrics of ReNuAl seem unfavorable, it should be noted that there is a significant degree of uncertainty surrounding the values of the CB cultivation and harvesting sections; the design of these systems has traditionally focused on biofuels applications. As a result, the scale and complexity of the equipment used is significantly higher than what should realistically be required for ReNuAl; this is especially true of the bioreactors. From Figure 3, we can determine that operation of the b-PBRs accounts for approximately 75% of the energy consumed by the process. This is largely driven by the mixing requirements of the reactors, which alone represent 24% of the TOC. This level of energy demand is reasonable at a biofuel production facility given the large volume b-PBRs must fit to accommodate the high production rates required. However, ReNuAl will use significantly smaller reactors, and, as a result, these will likely require less energy to be well-mixed. Similarly, the labor, maintenance, and replacement costs of the b-PBRs, which together account for 40% of the TOC, would likely be lower than the values we calculated for the same reason.

The preliminary environmental analysis shows that the water use impact is higher for ReNuAl than for current practices. This is unsurprising as CB cultivation operations have high water requirements due to the achievable

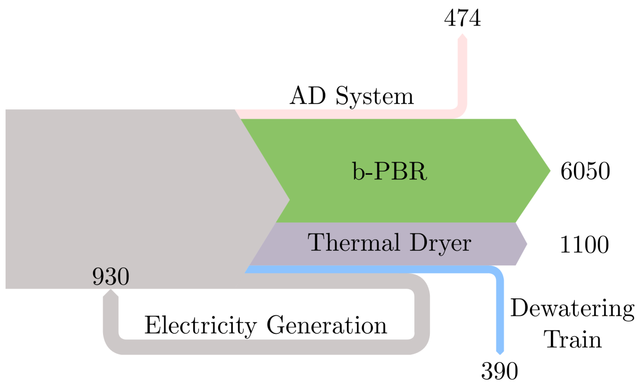

Figure 3. Yearly energy flows (in MW-hr) for the different sections of the ReNuAl process

titers being fairly low (approximately 1-2g/L). Manure spreading, on the other hand, does not require any additional water as manure has a moisture content of approximately 90%, and, after the removal of suspended solids, it can be easily pumped through a liquids distribution system. However, we also observe that ReNuAl generates 39% fewer GHG emissions than land application of manure. A significant portion of this reduction is due to the production of biogas. Under our framework, ReNuAl is able to export 429 tonnes/yr of methane which make it eligible to receive compensation from government-funded incentives like RIN credits from the EPA's renewable fuel standards program and low carbon fuel standard (LCFS) credits offered by the state of California. Applying the value of the RIN and LCFS credits, we determine that the process is able to generate an additional 600,000 USD/yr of revenue; this lowers the MSP of the CB fertilizer 18% to 6.33 USD/kg.

When we consider the release of nutrients to the environment from the land application of livestock waste with those from ReNuAl, we observe that our process has two distinct advantages. First, the N:P ratio of the biofertilizer more closely matches crop needs than manure, reducing the need for overapplication. Second, CB is a more stable medium and releases nutrients more gradually than manure [15, 16]; this significantly reduces the amount of nutrients carried away during rain events. The HABs caused by nutrient runoff result in the affected waterbodies not being usable for economic activities like fishing and recreation and, as a result, represent a loss for the surrounding communities. Previous studies focusing on the Upper Yahara have estimated these losses to have a cost of 74.5 USD/kg P [7]. Thus, if we apply an equivalent credit, we determine that we can generate an additional 789,700 USD/yr if a CB strain that is able to capture all of the P in the manure can be engineered. If we combine this with the revenue from the RIN and LCFS credits, the MSP of the CB can be reduced further to 4.45 USD/kg. It is important to note that this represents a best-case scenario and additional work must be done to determine nutrient uptake and leaching rates for the CB.

In addition to highlighting potential knowledge gaps as previously discussed, our framework allows us to understand the sensitivity of process economics to changes in various key parameters. For this analysis we considered the reactor batch time, the fraction of biogas sent to market, the reactor surface area to volume (SA:V) ratio, the light available to the bioreactors, and the P uptake of the CB. Note that this is not an exhaustive selection; rather, these choices are based on the variables we can meaningfully simulate using the current process model.

The results shown in Figure 4 (note we are including RIN and LCFS credits in the calculation of the MSP) indicate that the parameters associated with the design and operation of the b-PBRs, batch time and reactor SA:V ratio, have the largest impact on MSP. Given the cost of operating the reactors, these results are not surprising as these parameters directly affect the amount of reactor volume required.

After the batch time and SA:V ratio, the next most important variable to consider is the fraction of biogas sent to market. Due to the low value of electricity compared to the value of biogas and the cost of the electricity generation section, we observe a 13% decrease in the MSP when we export all of the biogas offsite. However, we should note that a significant portion of the revenue from the biogas comes from RIN and LCFS credits, and changes in policy can reduce the value of these credits.

From the variation in the light intensity, we can conclude that the process is not severely light-limited as shifting light availability up or down by 50% only moves the MSP -5% to +11% from the baseline. This indicates that in the current design it is the reactor surface area to volume ratio that limits the titer that can be achieved. This is due to shading effects which limit the distance that light can penetrate the vessel. As a result, the reactor design should be optimized before exploring methods for increasing light availability.

The results seem to indicate that lowering the P content of the CB might be favorable as this lowers the MSP. However, in this context, it is important to think about the value of CB which is dependent on its nutrient content. The reason the MSP decreases at lower P uptake values is because more of it must be produced to consume all of the available nutrients. As a result, on a nutrient content basis, the biomass is less valuable. A more appropriate question is then if this drop in value is matched by the drop in MSP. From Figure 4, we observe that the answer is no. Conversely, we also see that when the P content of the cells is increased, the MSP increases at a lower rate. Additionally, this decrease in throughput translates to a lower TCI and TOC. Thus, it might be possible to reverse this trend at higher P loading values.

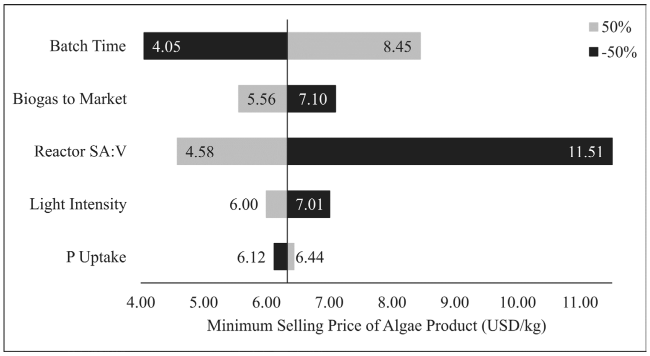

Figure 4. Change in MSP of CB product with changes to selected operating parameter

CONCLUSIONS AND FUTURE WORK

This study presented a framework for the capture and recycling of nutrients in livestock waste. The goal of this process, which we refer to as ReNuAl, is to provide a pathway towards a more circular economy that will allow livestock farmers to meet the projected increase in demand for animal products in a sustainable manner. An initial economic analysis of ReNuAl indicates that the produced biofertilizer is significantly more expensive than current synthetic fertilizers. However, we also determined that there is a significant degree of uncertainty around the economic values calculated for the b-PBR section due to the difference in scales that existing CB cultivation facilities operate at compared to ReNuAl. Thus, we are interested in developing protypes of the b-PBRs to better understand their operations and obtain more accurate performance metrics.

Our environmental analysis indicates that ReNuAl has the capability to reduce carbon and nutrient-based pollution. However, we also observe that CB cultivation has a high water requirement. As result, identifying methods that allow for high degrees of water reuse and recovery as well as locations that are not water-strained for deployment are important factors to consider moving forward. It is also important to note that these results are preliminary. Moving forward we will focus on improving the accuracy of these values by working with microbial, agronomy, and environmental science experts who can perform field trials to measure variables of interest like maximum attainable titer, nutrient uptake and leaching, and GHG emissions. Additionally, we will also extend our analysis by evaluating other environmental metrics and performing a sensitivity analysis on the energy sources used to power the process as previous studies have shown that changing the energy source to non-fossil alternatives can decrease the climate change impact [23].

Using our TEA model, we were able to identify key operating parameters that can have a significant impact on the viability of the ReNuAl process. Our results indicate that optimization of b-PBR design and operation, specifically vessel geometry and batch times, can significantly reduce the MSP of the biofertilizer. We also observe that by increasing P-uptake we can make a more nutrient-dense product that can be sold at a lower price (on a nutrient content basis) while also reducing capital and operating expenses. From these results we can conclude that developing fast-growing CB strains that have a high P content using a reactor with as high an areal mass density (high SA:V value) as possible will significantly improve the economics of ReNuAl. Additionally, this works demonstrates how a computational framework serves as a goal-oriented tool for determining promising directions that researchers can proceed in. Moving forward we are interested in exploring the impact of additional CB-specific traits that can potentially improve the economic and environmental performance of ReNuAl such as maximum harvest titer and settling velocity as well as the capacity of the organism to remove CO_2 and H_2S from the biogas stream; we plan to achieve this by making use of new experimental data to refine our existing process models. In other words, our future work centers around the integration of process and economic models with experiments to allow for continuous model improvement which in turn allows for the accurate identification of key variables and regions of diminishing returns.

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