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Economic and Environmental Analysis for Advancing Sustainable Management of Livestock Waste: A Wisconsin Case Study

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Abstract

Livestock waste may cause some air quality degradation from ammonia and methane emissions, soil quality detriment due to in-excess nutrients and acidification, and water pollution issues resulting from nutrient and pathogens runoff to water bodies, which leads to eutrophication, algal blooms, and hypoxia. Despite the significant environmental benefits by performing pollution management of these organic materials, the recovery of value-added products from livestock waste is not a current practice due to the high investment costs required and to the low market values being offered for the products that are recovered.

Therefore, we present a supply chain design framework to conduct simultaneous economic and environmental analysis of post-livestock organic material to value-added products. The proposed framework captures techno-economic and logistical issues and can accommodate diverse types of policy incentives obtained at federal and state levels, allowing stakeholders to conduct systematic studies on the effect of incentives on economic and environmental viability of different technologies. We apply the framework to a case study for dairy farms in the State of Wisconsin (U.S.). The framework reveals that, from a purely economic perspective, products recovered from dairy waste are not competitive at current market prices. We also find that incorporating current and potential U.S. government incentives in the form of Renewable Identification Numbers (RINs) and phosphorus credits can achieve economic viability of the recovery of liquefied biomethane and nutrient-rich products. On the other hand, current incentives for electricity generation (Renewable Energy Credits or RECs) would not achieve economic viability. The analysis also reveals that the best strategy to manage waste is to synergize the deployment of technologies that conduct simultaneous recovery of liquefied biomethane and nutrients.

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Keywords

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1. Introduction

Livestock waste (manure) generates significant air and water quality issues in the form of methane and pathogens emissions as well as nutrient runoff to water bodies, which ultimately leads to eutrophication, algal blooms, and hypoxia [1, 2]. Nutrient pollution is one of the leading causes of leading causes of water quality impairment in the United States [3]. Lake Erie, for example, faces persistent algal bloom issues due to phosphorus runoff. In the summer of 2014, the city of Toledo, Ohio issued a two-day water ban due to the formation of harmful algal blooms from which it draws drinking water. This resulted in about 500,000 people losing access to drinking water [4]. One strategy to contain nutrient runoff consists of processing the livestock waste to recover excess nutrients and with this balance nutrient budgets in endangered areas [5]. The nutrient-rich products (e.g. struvite which is a phosphorus-rich product) can then be sold to the market as a fertilizer [6] or can be transported to less endangered areas. Methane can also be recovered in gaseous or liquid form and can be used as a transportation fuel or to generate heat and electricity [7].

Despite the significant environmental benefits associated to waste processing, the recovery of value-added products from livestock waste is not commonplace at present due to the high investment costs required and to the low market values being offered for the recovered products. In case of electricity, for instance, utility companies purchase electricity at an average value of 0.04 USD/kWh [8]. For electricity recovered from livestock waste this value is insufficient to offset investment and operation costs of the processing units (particularly in small to medium farms; as see from our analysis in Table 4). Federal and state incentives such as the Renewable Energy Credits (RECs) and Renewable Identification Numbers (RINs) can help offset these costs and promote investment. However, selecting suitable recovery pathways is a complicated task because of the multiple products and technology options that need to be evaluated and because of complex transportation (logistical) issues.

Existing research studies have not addressed the problem of livestock waste management from a holistic (systems-wide) standpoint. Decisions are often based on techno-economic feasibility studies for individual technologies [9–14]. These techno-economic analyses consider the costs associated with the installation and operation of a variety of technologies such as anaerobic digestion in combination with nutrient recovery and biogas upgrading. They also consider the potential economic returns that can be obtained from product sales and objectives. These studies are site-specific and often assume a processing capacity that is equal to the waste generation capacity of the farm. Due to the economies of scale, however, production cost fluctuates significantly with farm sizes. This can make waste processing in smaller farms economically infeasible. A better option for such farms might be to transport the raw or preprocessed waste to larger centralized facilities to conduct final processing.

Such possibilities can be explored under a systems-wide approach that simultaneously determines technologies types and sizes as well as product transportation strategies.

Facility location studies in livestock waste processing reported in the literature explore the use of hub and spoke (semi-centralized) layouts [8] and centralized layouts [15]. The study in [8], for instance, proposes a hub and spoke processing configuration for dairy farms in the Kewaunee County in the State of Wisconsin (WI). The study proposes to recover nutrients and renewable natural gas that is cleaned and injected in a transmission pipeline. The location of the hubs (or the processing units) is determined by assigning the larger concentrated animal feeding operations (CAFOs) as hubs and the smaller farms as the spokes which transfer their dairy waste to the hubs. The spokes for a hub are selected by drawing a five-mile radius around the hub and refining the boundaries until a desired number of hubs are obtained. This approach presents a simple strategy for building a supply chain network. Another approach is to use a geographic information systems (GIS) based framework to determine the location of the processing facilities [16]. In such analysis, the location is determined by considering different factors such as distance of farms to transmission lines, natural gas pipelines, power plants, and roads. Economic and environmental aspects are also factored in these types of studies but they often assume a single technology option (due to inherent complexity associated to technology selection and sizing). The benefits of centralized biogas processing facilities have also been studied in the literature [15]. For swine manure management in North Carolina, for instance, it has been found that the most cost-effective solution is to design a supply chain with a single centralized directed biogas facility [15]. The selection of suitable supply chain configuration is a complex decision that is highly dependent on the spatial location of the dairy farms, the final destination of products, geographical prioritization, and on local economic (market) and policy conditions.

In this work, we use a multiproduct supply chain framework [17] to simultaneously conduct technology selection, sizing, and placement. The model captures transportation flows and conversion of multiple products across spatially dispersed CAFOs. We show that this framework can easily accommodate diverse types of material management incentives obtained at federal and state levels. These capabilities allow us to conduct systematic studies on the effect of incentives on economic and environmental viability of different technology types for the recovery of a diverse set of energy and nutrient products. Our analysis reveals that the optimal strategy to manage livestock waste from dairy farms in the State of Wisconsin is to perform biogas recovery and upgrading and nutrient recovery *simultaneously* (in the form of hybrid technologies). This strategy generates a high return on investment and helps target both air and water quality issues.

2. Current Incentives

The electricity generated from any renewable source (e.g., wind, solar, biomass, and biogas) is currently incentivized in the U.S. by using RECs [18]. Under this system, every unit (MWh) of renewable electricity generated receives an REC. The producer of renewable energy can then sell the RECs either in a compliance market or in a voluntary market (Figure 1). Compliance markets are generated when an individual state introduces a

Renewable Portfolio Standard (RPS) that mandates the utility companies generate a portion of their total energy from renewable sources. For example, the State of California established an RPS in 2002 to achieve 50% of its total energy generation from renewable sources by 2050 [19]. To achieve this goal, California has mandated a gradual increase in energy generation from renewable sources (requiring 33\% by 2020; 40\% by 2024; 45\% by 2027; 50\% by 2030 [20]. Utility companies that cannot achieve this goal have an option to buy the RECs from renewable energy producers. This results in the formation of a compliance market for RECs where the value of an REC varies with supply and demand. The value of one REC in a compliance market has historically fluctuated between 0.50 USD/MWh to 60 USD/MWh [21]. State regulations play an important role in driving demand values and thus influencing the price of RECs. For example, the State of New Jersey has a subprogram in place to support electricity production from solar energy and it has set a goal to achieve 4.1\% of energy generation from solar energy by the year 2027–2028 [22]. The RECs corresponding to solar energy are termed SRECs and can have a market value as high as 600 USD/MWh [21]. Voluntary markets arise when customers volunteer to purchase RECs to support the generation of energy from renewable sources. In a voluntary market, the value of one REC has varied between 0.50 USD/MWh and 2.00 USD/MWh [21].

Another method for incentivizing renewable energy generation is through RINs for transportation fuels. As per the Renewable Fuel Standard (RFS) created under the Energy Policy Act of 2005, the producers of non-renewable fuels are required to blend a certain amount of renewable fuels in their final products. Thus, when a non-renewable fuel is produced, a Renewable Volume Obligation (RVO) is generated, which needs to be fulfilled by purchasing RINs. Similar to RVOs, RINs are generated when a renewable fuel is produced. The concepts of RVO and RIN are also based on supply and demand. RVO is the demand value required to be fulfilled on the generation of a non-renewable fuel, while RIN is the supply value that can satisfy this demand. One RIN corresponds to one gallon of renewable fuel. The RFS categorizes RINs into four classes of fuels: biomass-based diesel, cellulosic biofuel, advanced biofuel, and total renewable fuel (Figure 1). Each of these classes has an associated RIN. The RVO includes requirements for these different RINs. In the context presented in this work, the fuels produced from livestock waste fall under the category of cellulosic biofuels [23]. There are limited sources of cellulosic biofuels (i.e., the demand for cellulosic biofuels is higher than the supply) and thus have a high value of around 2.00 USD/RIN. In cases where the non-renewable fuel generators cannot find cellulosic RINs to meet their requirement, they have an option to buy Cellulosic Waiver Credit (CWC). The CWCs are made available by the U.S. Environmental Protection Agency (U.S. EPA) when the projected volume of cellulosic biofuel production is less than the applicable volume of cellulosic biofuel set forth in the Clean Air Act. The U.S. EPA determines the price of CWCs using a formula specified in the Clean Air Act [24]. For the year 2017, the value of a single CWC is 2.00 USD [25].

Renewable electricity production tax credits (PTC) have been used in the past in the U.S. to help the development of energy from renewable sources such as wind, geothermal, and biomass [26]. Until 2015, a full PTC credit of 2.3 cents/kWh (0.023 USD/kWh) was given to electricity generated from sources such as wind, closed-loop biomass (any organic material from the plant which is planted exclusively for energy generation), and geothermal. A half credit of 1.2 cents/kWh (0.012 USD/kWh) was given to technologies such as open-loop biomass (e.g. agricultural livestock waste), municipal solid waste, and hydropower.

In April 2017, the Agriculture Environmental Stewardship Act of 2017 was introduced in the U.S. Senate. This program proposed to introduce energy tax credits through 2021 for qualified biogas qualified biogas properties and qualified manure resource recovery properties [27]. The qualified biogas properties include anaerobic digesters that convert biomass to a gas with at least 52\% methane. Manure resource recovery includes technologies that recover phosphorus and nitrogen by separating at least 50% of the mass of phosphorus and nitrogen.

Incentives for nutrient recovery provide a mechanism to mitigate water quality issues. The State of Virginia, for instance, runs a nutrient trading program in the Chesapeake Bay watershed where Phosphorus credits (P credits) have a value of 10.10 USD/lb P (22.04 USD/kg P) [28]. Nutrient trading can also allow one source to meet its regulatory obligations by using pollutant reductions created by another source with lower pollution controls [29].

3. Multi-Product Supply Chain Model

In this section, we describe the supply chain modeling framework used to guide technology sizing and placement and transportation decisions. We will use this framework to analyze the impact of using different policy incentive mechanisms on the economic and environmental viability of different technologies.

We consider a network that comprises a set of nodes $\mathcal{N}$, links (arcs) $\mathcal{F}$, products $\mathcal{P}$, out-of-network sources $\mathcal{S}$, and out-of-network sinks (demand) $\mathcal{D}$. Associated to each link $l \in \mathcal{F}$, there is a one-directional flow $f_\ell \in \mathbb{R}_+$ (where $\mathbb{R}_+$ is the non-negative orthant) that has the following attributes: product type $\text{prod\_ink}[\ell] \in \mathcal{P}$ (e.g., biogas, electricity, struvite), capacity $\text{cap\_link}[\ell] \in \mathbb{R}_+$, transportation cost $\text{cost\_link}[\ell]\left(\text{ or } \alpha_\ell^f\right) \in \mathbb{R}_+$, sending node $\text{snd\_lnk}[\ell] \in \mathcal{N}$, and receiving node $\text{rec\_link}[\ell] \in \mathcal{N}$. We use attributes to define subsets and nested set partitions. In particular, the set $\mathcal{F}_n^{in} := \{\ell | \text{rec\_Iink}[\ell] = n\}$ is the set of all flows entering node $n \in \mathcal{N}$. Similarly, the set $\mathcal{F}_n^{out} := \{\ell | \text{snd\_link}[\ell] = n\}$ is the set of all flows leaving node $n \in \mathcal{N}$. We also define the nested subsets for entering flows $\mathcal{F}_{n,p}^{in} \subseteq \mathcal{F}_n^{in} \subseteq \mathcal{F}$ where $\mathcal{F}_{n,p}^{in} := \left\{\ell | \text{rec\_link}[\ell] = n, \text{prod\_link}[\ell] = p\right\}$ and note that $\cup_{p \in \mathcal{P}} \mathcal{F}_{n,p}^{in} = \mathcal{F}_n^{in}$. We use similar definitions to construct subsets for the leaving flows $\mathcal{F}_{n,p}^{out} \subseteq \mathcal{F}_n^{out} \subseteq \mathcal{F}$.

Associated to each out-of-network source $i \in \mathcal{S}$ is a flow $s_i \in \mathbb{R}_+$ with attributes: product type $\text{prod\_src}[i] \in \mathcal{P}$, source capacity $\bar{s}_i := \text{cap\_src}[i] \in \mathbb{R}_+$, node $\text{node\_src}[i] \in \mathcal{N}$, and cost $\alpha_i^s := \text{cost\_src}[i] \in \mathbb{R}_+$. Similarly, associated to each out-of-network sink (demand) $j \in \mathcal{D}$ is a flow $d_j \in \mathbb{R}_+$ with attributes: product type $\text{prod\_sink}[j] \in \mathcal{P}$, sink capacity

$\bar{d}_j$ ≔ cap_sink[j] $\in \mathbb{R}_+$, node node_sink[j] $\in \mathcal{N}$, and cost α_j^d ≔ cost_sink[j] $\in \mathbb{R}$. We use attributes to define the nested sets $\mathcal{S}_{n,p} \subseteq \mathcal{S}_n \subset \mathcal{S}$ with $\mathcal{S}_n$ ≔ {i| node _src[i] = n} (i.e., all sources attached to a node n) and $\mathcal{S}_{n,p}$ ≔ {i|node_src[i]=n, prod_src[i] =p} (i.e., all sources of product p attached to node n). We can follow a similar reasoning to define the nested sets $\mathcal{D}_{n,p} \subseteq \mathcal{D}_n \subset \mathcal{D}$.

We formulate the *supply chain design* problem by defining a set of candidate technology types $\mathcal{T}$ that can be installed at a set of predefined candidate network nodes (e.g., CAFOs). We use the binary variable $y_{t,n} \in \{0,1\}$ to indicate that technology $t \in \mathcal{T}$ is installed at node $n \in \mathcal{N}$. Each technology $t \in \mathcal{T}$ has a set of transformation factors $\gamma_{t,p}$, reference product $p'(t)$ = prod_tech [t] (e.g. waste), capacity $\bar{g}_t$ = cap_tech[t], as well as investment α_t^I ≔ cost_tech[t] $\in \mathbb{R}_+$ and operational cost α_t^O ≔ opcost _tech[t] $\in \mathbb{R}_+$. The transformation factors $\gamma_{t,p}$ capture the generation/consumption of products $p \in \mathcal{P}$ in technology $t \in \mathcal{T}$ and represent the amount of product p that is generated/consumed per unit of reference product $p'(t)$ consumed/generated.

We express the product balance equations that capture all the possible technologies to be installed at node $n \in \mathcal{N}$ as:

$$\left(\sum_{i \in \mathcal{S}_{n,p}} s_i + \sum_{\ell \in \mathcal{F}_{n,p}^{in}} f_\ell\right) - \left(\sum_{j \in \mathcal{D}_{n,p}} d_j + \sum_{\ell \in \mathcal{F}_{n,p}^{out}} f_\ell\right) + \sum_{t \in \mathcal{T}} \gamma_{t,p} r_{n,p'(t),t} = 0, \quad (n,p) \in \mathcal{N} \times \mathcal{P} \tag{3.1a}$$

$$\left(\sum_{i \in \mathcal{S}_{n,p'(t)}} s_i + \sum_{l \in \mathcal{F}_{n,p'(t)}^{in}} f_\ell\right) = \sum_{t \in \mathcal{T}} \left(r_{n,p'(t),t} + u_{n,p'(t),t}\right), \quad n \in \mathcal{N}. \tag{3.1b}$$

Where $r_{n,p'(t),t}$ and $u_{n,p'(t),t}$ are the processed and unprocessed flows at node n for technology t and associated reference product $p'(t)$. We only allow at most for one technology to be installed per node, which can be formulated using the constraint:

$$\sum_{t \in \mathcal{T}} y_{t,n} \le 1, n \in \mathcal{N}. \tag{3.2}$$

The processed flow of technology t is bounded by the capacity of the installed technology:

$$0 \le r_{n,\,p'(t),\,t} \le \left|\gamma_{n,\,p'(t)}\right| \cdot \bar{g}_t \cdot y_{t,\,n}, n \in \mathcal{N}, t \in \mathcal{T} \quad (3.3)$$

This implicitly imposes a constraint on the generation/consumption flows for the technologies $g_{n,p'(t),t}$. The unprocessed flows $u_{n,p'(t),t}$ must satisfy:

$$0 \le u_{n,\,p'(t),\,t} \le \bar{u}_{n,\,p'(t),\,t} \cdot y_{t,\,n}, n \in \mathcal{N}, t \in \mathcal{T}, \quad (3.4)$$

where $\bar{u}_{n,\,p'(t),\,t}$ is a suitable upper bound.

Capacities on flows as well as out-of-network sources and sinks are given by:

$$0 \le f_{\ell} \le \bar{f}_{\ell}, \ell \in \mathcal{F} \quad (3.5a)$$

$$0 \le s_i \le \bar{s}_i, i \in \mathcal{S} \quad (3.5b)$$

$$0 \le d_j \le \bar{d}_j, j \in \mathcal{D}. \quad (3.5c)$$

The total supply, demand (or product revenue), and transportation costs in the network are given by:

$$\varphi_r = \sum_{j \in \mathcal{D}} \alpha_j^d d_j \quad (3.6a)$$

$$\varphi_s = -\sum_{i \in \mathcal{S}} \alpha_i^s s_i \quad (3.6b)$$

$$\varphi_t = -\sum_{\ell \in \mathcal{F}} \alpha_{\ell}^t f_{\ell} \quad (3.6c)$$

Investment and operational costs are expressed in terms of the binary variables $y_{t,n}$ as:

$$\varphi_I = -\sum_{t \in \mathcal{T}} \sum_{n \in \mathcal{N}} \alpha_t^I y_{t,n} \quad (3.7a)$$

$$\varphi_O = -\sum_{t \in \mathcal{T}} \sum_{n \in \mathcal{N}} \alpha_t^{opt} y_{t,n}. \quad (3.7b)$$

The supply chain design problem can thus be cast as the following multi-objective mixed-integer linear program (MILP):

$$\max\left\{\varphi_r, \varphi_I, \varphi_s, \varphi_t, \varphi_O\right\} \quad (3.8a)$$

$$\text{s.t.} \quad (3.1) - (3.7). \quad (3.8b)$$

The objective function is the total profit in the supply chain network, given by the difference of the total revenues collected in the supply chain φ_D and the costs associated to supplies, transportation flows, and technology operations.

In the proposed model, we allow the value of the demands α_j^d to be either positive or negative. When the value is positive, it indicates that there is an economic incentive to satisfy the demand (we thus seek to maximize the demand served d_j to the associated node). In other words, product flows are attracted to the demand node. On the other hand, when the demand value is negative, it indicates that there is an incentive to not satisfy the demand at the associated node (the product flows are pushed away from the demand node). In this case, the demand d_j acts as a slack (residual) variable that we seek to minimize. Negative demand values can be used to model environmental remediation effects because we can consider the environment as a sink, consumer, or "stakeholder" that demands a product (waste, digestate) at a negative price. This also highlights the fact that, in our framework, products always have a final destination (i.e., for either consumption or for storage in the environment) and the values for supplies and transportation costs are all assumed to be positive. Consequently, maximizing the social welfare minimizes supply, transportation, and operational costs.

The model notations and node-level interactions are sketched in Figure 2. Here, we consider a candidate node (e.g. a dairy farm) in the supply chain network, where the waste generated on-farm is processed to recover electricity and cake$_1$ (a nutrient rich product). The waste generated on-farm is a part of the source set $\mathcal{S}_n$. Other dairy farms in the supply chain network can also transfer their waste to this candidate node for processing. Such waste flows are captured as a part of the incoming flow to the node $\left(\overrightarrow{\mathcal{F}}_{n,\ \text{waste}}\right)$. Similarly, other farms can also transfer electricity and cake$_1$ for use at the candidate node. These flows are also captured under the set of incoming flows $\overrightarrow{\mathscr{F}}_n$. The multiproduct model selects the optimal technology from a wide array of candidate technologies available for waste treatment. For this illustration, the selected technology consists of an anaerobic digester followed by an electricity generator for the production of electricity. The digestate obtained from anaerobic digestion is processed through a filter to recover cake_1. The products used on-site or sold at this farm are considered under the demand set $\mathscr{D}_n$. The remaining amount of products sent to other nodes in the network are captured through the set of outgoing flow $\left(\overleftarrow{\mathscr{F}}_n\right)$.

In summary, the problem statement for the network design problem is as follows: Given a set of products $(\mathscr{P})$, sources $(\mathscr{S})$, sinks $(\mathscr{D})$, candidate locations $(\mathscr{N})$, and candidate technologies $(\mathscr{T})$ the goal is to determine the optimal locations for siting technologies $(y_{t,n})$, product flows $\left(f_\ell\right)$, and resource allocations (s_i and d_j) in the network that are a Pareto optimal solution of problem (3.8).

4. Case Studies

We use the proposed framework to investigate optimal technology deployment strategies to recover value-added products from waste generated at the 100 largest dairy CAFOs in the State of Wisconsin [30]. We begin with a purely economic analysis that does not factor in incentives. We perform this analysis for each product independently and determine the market value at which it becomes economically feasible to recover such product. We then formulate a problem in which we include a wide range of product recovery technologies to identify optimal technology combinations. Finally, we incorporate incentives associated with the recovery of renewable energy and fuels (e.g. RECs, RINs) and nutrient credits to understand how such incentives alter the optimal technology landscape to achieve water and air quality improvements.

We consider different nutrient recovery and biogas upgrading technologies. A key observation is that all these routes require anaerobic digestion (AD). Anaerobic digestion takes dairy waste as the input and produces biogas and $\text{digestate}_{\text{AD}}$. The produced biogas can be upgraded to recover value-added products such as electricity and transportation fuels. The $\text{digestate}_{\text{AD}}$ can be treated to recover nutrients such as phosphorus (P) and nitrogen (N). Figure 3 illustrates the technology options considered. To illustrate the conversion efficiencies (yields) for various technologies, we begin with a base value of 100 kg of dairy waste. This dairy waste is assumed to include wash water used at dairy farms along with the excreted manure. The total solids content of this dairy waste is considered to be 7\%. The composition of the excreted manure is calculated by considering a herd consisting of 72% lactating cows, 4.5% dry cows, 23.3\% heifers, and 0.2\% calves and using the corresponding N, P, TS (total solids), and VS (volatile solids) values reported in Lorimor et al. [31]. The water content of excreted manure is 88% (i.e. a TS of 12%). We consider a mass dilution to 93% water content due to the addition of wash water, resulting in the final composition of dairy waste (reported in Table 1).

Anaerobic digestion of 100 kg of the dairy waste produces 1.24 standard cubic meter (scm) of biogas and 98.83 kg of digestate$_{AD}$. This amount of biogas produced is estimated by considering that one kg of VS results in 0.22 scm of biogas [32]. The dairy manure has a VS content of 80% of TS [32]. Consequently, 100 kg of waste contains 5.61 kg of VS, which results in the production of 1.24 scm of biogas. This biogas (containing 60% CH_4 and 39% CO_2 on a volume basis) is assumed to have a density of 1.15 kg/m^3 [33]. The amount of digestate$_{AD}$ produced is then estimated by a mass balance analysis.

The biogas can either be used for heating purposes or for electricity generation. The amount of electricity generated is based on the CH_4 content of the biogas. CH_4 has a heating value of 1000 BTU/ft^3 (37.3 MJ/m^3). The produced biogas has 60% CH_4 on a volume basis. Assuming a thermal efficiency of 28%, one kWh of electricity generation corresponds to 12 ft^3 (0.345 scm) of CH_4. We thus estimate that 2.18 kWh of electricity can be generated from 100kg of dairy waste.

An alternative to generating electricity is the recovery of either biomethane or transportation fuels from the biogas. Both of these products require further cleaning of raw biogas to remove impurities such as H_2O, H_2S, and CO_2. The H_2O can be removed by condensation, while the H_2S is removed using an iron sponge technology [12]. The clean biogas can be further upgraded to remove CO_2 by using a scrubbing technology to produce pipeline quality biomethane (0.74/100 kg waste) [12]. The amount of biomethane produced is estimated by considering a yield factor of 0.596 scm of biomethane per scm of biogas [34]. The produced biomethane can be pumped directly into the national natural gas pipeline. Yet another alternative is to liquefy the biomethane to produce liquefied biomethane (LBM). This results in 0.31 gal (1.17 liters) LBM. The yield of LBM is based on the assumption that 84 ft^3 of biomethane correspond to one gal of LBM [12].

For nutrient recovery, we consider five technology variants that take digestate$_{AD}$ as the input and produce P-concentrated products (cakes or struvite) and digestate as the output products. The conversion efficiencies and associated investment and operational costs have been estimated by using the models reported in Martin et al. [35]. The first technology considered is based on reactive filtration where a metal slag is used as the filter medium. This technology produces 12.22 kg of cake$_1$ containing 0.57% P. The second technology is centrifugation with pretreatment, where a mixture of $CaCO_3$ and $FeCl_3$ is added to enhance the separation efficiency of P. A total of 37.73 kg of a nutrient-rich cake (cake$_2$) is produced containing 0.21% P. The next technology considered is coagulation flocculation, where first the digestate$_{AD}$ in the form of suspension is destabilized by reducing attractive forces. A flocculation process is then carried out to form flocs from the previously destabilized colloids, and this results in their subsequent precipitation resulting in 15.23 kg of cake$_3$ which has a P content of 0.52%. The next technology is a fluidized bed reactor (FBR) where struvite ($NH_4MgPO_4.6H_2O$) is precipitated by the addition of $MgCl_2$. The advantage of this technology is that struvite is a solid with high nutrient density (which makes it more convenient to transport compared to transporting waste) and can be used as a slow-release fertilizer without any post-processing [36]. FBR produces 0.62 kg of struvite (containing 12.57% P) per 98.83 kg of input digestate$_{AD}$. The final nutrient recovery technology that we consider is a continuous stirred tank reactor (CSTR), where the final product also contains struvite but with a P content of 1.22%. Since the residence time in the CSTR is large, it is not necessary to use a pre-mixing tank (as in the case of FBR) and $MgCl_2$ is added directly to the reactor. Consequently, 5.86 kg of struvite + solids is formed in one step in the CSTR. The amount of digestate produced from the above-listed nutrient recovery technologies is estimated via mass balance analysis.

4.1 Pure Economic Analysis

We first investigate the waste treatment problem from a purely economic perspective. The objective is to find a technology deployment strategy that maximizes the economic returns without including any incentives. Penalties associated with nutrient emissions are also not imposed in this analysis. We assign a market value to all the products (Table 2). We assume that utility companies buy electricity at an average price of 0.04 USD/kWh [8]. In case of biogas, when used for heating purposes, the associated cost is calculated based on its heating value. In our analysis, the untreated biogas after AD has a CH_4 content of 60% on a volume basis. Thus one standard cubic meter (scm) of biogas has a heating value of 21,333 BTU or 0.021 MMBTU. Based on the market value of natural gas at 2.25 USD/MMBTU [37], we estimate the value of biogas to be 0.048 USD/scm

Biomethane is obtained after the biogas is upgraded to remove H_2O, H_2S, and CO_2 to achieve the purity of pipeline quality natural gas. This biomethane can then be pumped to the national natural gas pipeline. The value of biomethane is assumed to be the same of natural gas (0.15 USD/scm). Liquefied biomethane is obtained by the liquefaction of biomethane. Its value is assumed to be the same as that of liquefied natural gas (LNG) at 1.0 USD/gal [12]. The value for nutrient-rich cakes (i.e. $cake_1$, $cake_2$, and $cake_3$) are estimated to be 15 USD/ton, 4.9 USD/ton, and 12.5 USD/ton, respectively, based on the analysis provided in Hernandez et al. [38]. The average market value of struvite is considered to be 800 USD/ton [39]. The corresponding market value for struvite + solids is estimated to be 77.3 USD/ton based on its relative P concentration of 1.22% with respect to P concentration of struvite of 12.57%. The livestock waste has been assigned a market value of zero. Similarly, the effluent streams $digestate_{AD}$, $digestate_1$, $digestate_2$, $digestate_3$, $digestate_4$, and $digestate_5$ have been assigned a market value of zero in this case. This is equivalent to assuming that the untreated livestock waste and the effluent streams are spread on the field and there is no disposal cost associated with this.

We also report the carbon efficiencies corresponding to each final product recovered as described in Table 2. Carbon efficiency is a green chemistry indicator that represents the percentage of carbon in the reactants that remain in the final product [40]. The majority of carbon from the waste is captured in nutrient-rich products (85%) while the remaining carbon is recovered in biogas or related products (10% - 15%). These values are computed by a simple mass balance analysis. Nutrient recovery is thus a major source of carbon capture compared to biogas recovery. The input waste has a carbon content of 3.65% (Table 1). The biogas generated after anaerobic digestion has majority carbon in the form of CH_4 and CO_2 corresponding to 15% of the total carbon in the input waste. Further processing of biogas to produce biomethane and liquefied biomethane involves removal of CO_2, thus resulting in a reduced carbon efficiency (10%) for these products. The remaining carbon of the input waste is considered to remain in the digestate$_{AD}$ after anaerobic digestion. The models reported in Martin et al. [35] consider that carbon present in digestate$_{AD}$ is recovered with the nutrient-rich products. Table 2 also reports the P content of the input waste and the various nutrient-rich products based on the models reported in Martin et al. [35]. We also report the phosphorus (P) efficiencies associated with each product. This is similar to the concept of carbon efficiency. P efficiency is the percentage of phosphorus in the reactants that remains in the final product. It is interesting to note that even though struvite has a high P content (12.57%), its P efficiency (90%) is lower than that of cake$_2$ (95%) and cake$_3$ (99%) because the amount of struvite produced per unit mass of waste is less compared to the yield factors associated with that of cake$_2$ and cake$_3$, thus reducing the total P recovered in the process.

In our studies, we consider the technologies identified in Table 3 to create the set of candidate technologies T. Two different capacity variants have been considered for each technology. These are quantified in terms of the animal unit (AU) equivalent of the waste they can process. The AU is a standard unit used in calculating the relative grazing impact of different kinds and classes of livestock. It is defined as an animal equivalent of 1,000 pounds live weight. For reference, a single lactating dairy cow weighs about 1,400 pounds or 1.4 AUs. We consider technologies with processing capacities of 5,000 and 10,000 AUs. The data for investment and operation costs were obtained from a variety of sources. In case of anaerobic digestion, we estimate the investment cost based on the cost projection formula given in Meyer and Powers [41].

The operating cost for an anaerobic digester is assumed to be 2.4% of the investment cost [14]. The cost of technologies (t2 and t26) for biogas production, followed by electricity generation is estimated from the prices reported in [42] for a dairy farm in Indiana. The capital cost is reported to be 12 million USD [42] for a two-stage mixed plug flow digester (capacity corresponding to 9,000 cows) with engine and generator [23]. The operating costs are reported to be 600,000 USD per year. We scale these costs using the six-tenths factor rule [43] to estimate the cost associated with technologies t_2 and t_{26} having capacity corresponding to 5,000 and 10,000 AU, respectively. We scale the operating costs also using the six-tenths-factor rule since the detailed process data are not reported for these technologies. Also, since the operating cost is usually 10% of the capital cost (i.e. proportional to the capital cost), we assume that it follows similar scaling relationship as that of the capital cost. Similarly, the cost of biogas cleaning and upgrading to pipeline quality biogas (biomethane) or liquefaction to liquefied biomethane is estimated using the six-tenth rule from the costs reported in Krich et al. [12]. Krich et al. [12] estimate the technology cost for dairy farms in California based on the data collected from biogas upgrading plants in Sweden. For the case of nutrient recovery technologies (filtration, centrifugation, coagulation flocculation, FBR, and CSTR), the cost data were based on the models reported in Martin et al. [35].

A common limiting factor for the economic viability of waste treatment technologies is the competition from non-renewable sources that offer the same product at a much lower price. In order to analyze how production costs for product recovery from dairy waste compare to the current market values, we perform a market value analysis. First, we calculate the total production cost per unit product by accounting the investment and operating cost data (Table 4). Because of economies of scale, the per-unit cost associated with a high capacity technology like 10,000 AU is less than the cost associated with a lower capacity technology like 5,000 AU. For example, the production cost of electricity, when a technology with a 10,000 AU capacity is installed, is USD 0.11/kWh while in case of a technology with a 5,000 AU capacity, the production cost is USD 0.22/kWh. These prices do not account for transportation logistics.

In order to include the cost associated with waste transportation, we run the supply chain model [17] for each product recovery technology. We execute this analysis by limiting the list of candidate technologies to only the ones that recover the particular product being analyzed. For example, when analyzing the market value for electricity generation, the only candidate technologies that are considered are t_2 and t_{26}. For most of the products being considered, the market value is too low to justify waste processing. Thus, the optimal solution (from an economic perspective) is to do nothing and leave the waste untreated. We then gradually increase the value of the product to estimate the price at which the model finds it economically feasible to recover the product i.e. a solution that maximizes the total revenue from the sale of recovered products (φ_r) while minimizing the associated investment (φ_I), operational (φ_o), and transportation cost (φ_t). These costs are expressed in per year basis and the equipment life is considered to be 20 years in order to calculate the annualized investment cost. The objective function is to maximize the total profit including the total revenues (φ_r) obtained from individual product sale ($\varphi_{r,p}$):

$$\max \quad \varphi_r + \varphi_I + \varphi_O + \varphi_t \qquad (4.9a)$$

$$\text{s.t.} \quad (3.1) - (3.7) \qquad (4.9b)$$

The price analysis determines the optimal break-even cost that accounts for transportation costs along with the economies of scale. From Table 4 the break-even value associated with recovering electricity is 0.18 USD/kWh while the utility companies usually offer USD 0.04/kWh to purchase electricity. This reveals that it is generally not economically advantageous for dairy farmers in the U.S. to recover electricity from manure. The estimated break-even electricity cost also explains why renewable energy recovery has been economically feasible in countries such as Spain, Germany, and Denmark where the average value of electricity is 0.30, 0.35, and 0.40 USD/kWh, respectively.

The break-even values listed above assumes single product recovery. We now expand our analysis to consider all product recovery options and allow the model to make a decision about which sets of product should be recovered and on which technologies. In our study, we allow for some technologies to be synergized to recover multiple products simultaneously. Specifically, biogas upgrading can be combined with nutrient recovery to recover energy and nutrient-rich products. Since anaerobic digestion is the common first step in both biogas upgrading and nutrient recovery, the overall production costs for the final products can be brought down by synergizing these technologies. For this case study, we expand the list of candidate technologies to allow for the combination of such technologies. The candidate technologies listed in Table 3 consider all combinations possible between biogas upgrading and nutrient recovery. Note that this list also includes the single product recovery options to allow the model to select between synergizing technologies or recovering single products. The model uses the same objective function and constraints in Eq. 4.9 and uses the expanded list of candidate technologies as shown in Table 3. This case finds that leaving the waste unprocessed (do-nothing) is the best strategy from an economic perspective. This is because the market values for all the value-added products are lower than their respective production costs (Table 4). Moreover, we conclude that synergizing technologies is not sufficient to achieve economic viability.

4.2 Effect of Incentives

In this section, we analyze the effect of current incentives such as the RECs, RINs, and P credits on the economic viability of waste processing technologies.

4.2.1 Renewable Energy Credit (REC) Analysis—We use the proposed model to estimate the value of the REC incentive required to make electricity recovery an economically attractive option. This analysis is different from our analysis on market values (Section 4.1) as we now consider all 48 candidate technologies listed in Table 3. Thus, for the model to select electricity recovery technologies, the profits obtained from electricity generation not only need to be economically viable, but also should also achieve the highest economic returns compared to other product recovery options. The objective is to maximize the annualized profit including the revenue obtained from REC credits ($\varphi_{r,\,REC}$):

$$\max \quad \varphi_r + \varphi_{r,\,REC} + \varphi_I + \varphi_O + \varphi_t \qquad (4.10a)$$

$$\text{s.t.} \quad (3.1) - (3.7) \qquad (4.10b)$$

In our studies, we gradually increase incentives for electricity generation, as shown in Table 5. We begin by introducing REC incentives for every MWh of electricity generated. As shown in Table 5, the optimal supply chain does not recover electricity until the REC value is increased to 200 USD/MWh (0.2 USD/kWh). This is about 400% higher than the purchase price of electricity by utility companies (0.04 USD/kWh). Clearly, this is a high value and, even with such a high value, the return on investment (ROI) is low (1.92%). To obtain an acceptable investment and a shorter payback period, the REC value needs to be further increased (see Table 5). Such a heavy incentive strategy is not economically sustainable since it makes the entire waste processing infrastructure heavily dependent on external incentives.

Another interesting result found is that increasing the REC incentive above 500 USD/MWh does not significantly increase the amount of electricity recovered. The largest possible amount of electricity that can be generated by processing all the waste (i.e. $\varphi_{r,\text{waste}}$ = 100%)

is 1.67×10^5 MWh/yr. This value corresponds to 0.25% of the total electricity demand by the State of Wisconsin. From the point of view of Renewable Fuel Standard (RFS) for the state, this percentage is negligible. According to the RFS established in 1998, the State of Wisconsin had set a goal to reach 10% of the total energy generation be from renewable sources by the year 2015. Clearly, electricity generation from dairy waste does not contribute a significantly to achieve such goals.

4.2.2 Renewable Identification Number (RIN) Analysis—We now analyze the effect of introducing incentives associated with the production of renewable transportation fuel. These are known as the RINs (Renewable Identification Numbers). As described in Section 2, the liquefied biomethane generated from dairy waste is incentivized under the Cellulosic RINs category. In years when the projected supply for the cellulosic RINs is less than the projected demand value, CWC values are declared by the U.S. Environmental Protection Agency (EPA). The CWC for the year 2017 is 2 USD/gal of liquefied biomethane produced (Section 2). We perform our analysis around this value of 2 USD/gal and evaluate the return on investment (ROI) for the project. The objective is to maximize the annualized profit including the revenue obtained from RIN credits ($\varphi_{r,RIN}$):

$$\max \quad \varphi_r + \varphi_{r,RIN} + \varphi_I + \varphi_O + \varphi_t \qquad (4.11a)$$

$$\text{s.t.} \quad (3.1) - (3.7) \qquad (4.11b)$$

With a RIN value of 2 USD/gal, the supply chain framework does find it economically feasible to recover LBM and make a profit (Table 6). The ROI, however, is also rather low for this case (5.24%), resulting in a payback period of 19 years. Similarly, for a lower RIN value of 0.5 USD/gal, it is economically feasible to recover LBM but the payback period is larger than the assumed project life of 20 years. Increasing the RIN value helps bring down the payback period to about 10 years. The results in Table 6 also reflect the stable nature of the solution (i.e. increasing the RIN value results in a gradual increase in the ROI). We see, however, that the revenue collected from RINs is of the same order of magnitude as the revenue obtained from product sales, in indicating that the system will be heavily reliant on incentives. We also highlight that the revenue collected from RINs is in fact money invested by federal and local governments to incentivize technologies. Interestingly, we see that the investment needed to incentivize technologies via RECs or RINs (to achieve a similar ROI of 10%) are quite similar (on the order of 60–70 MUSD/yr).

One drawback associated to the recovery of LBM is that it cannot be stored for an extended period. In particular, evaporation losses make it economically infeasible to store LBM for more than a week. LBM storage pressure varies with the size of the storage tank: large tanks have a very low pressure of less than 5psig [0.3 barg], while smaller tanks (70,000 gallons and less), can have pressure between 5 psig [0.3 barg] to over 250 psig [16 barg]. LBM must be maintained cold (at least below −177°F [−83°C]) to remain a liquid, independent of pressure [46]. Thus, for LBM recovery based networks to be viable, there should be a stable customer base that can utilize the LBM soon after production. One example of this is using LBM as a fuel for the manure hauling trucks.

4.3 Phosphorus Credits Analysis

In our analysis, we consider the reduction in the P discharge brought by the recovery of nutrient-rich products to generate P credits at a dairy farm. A standardized quality specification of the recovered P is needed in order to regulate such product recovery based nutrient trading program. For this analysis, we consider that all the nutrient-rich products ($cake_1$, $cake_2$, $cake_3$, struvite, and struvite + solids) are eligible to claim P credits.

Since different nutrient recovery products ($cake_1$, $cake_2$, $cake_3$, struvite, and struvite + solids) have different P concentrations (0.57%, 0.21%, 0.52%, 12.57%, and 1.22%, respectively), their recovery will generate different P credits. We use the optimization model to decide which nutrient recovery option will generate highest profit given the associated production and logistical costs. No other incentives (such as RECs and RINs) are included in this analysis. The goal is to study the impact of nutrient credits on the overall project economics. As shown in Table 7 we test different values of P credits. The objective function for this case study is to maximize the annualized profit including the revenue generated from P credits ($\varphi_{r,P}$):

$$\max \quad \varphi_r + \varphi_{r,P} + \varphi_I + \varphi_O + \varphi_t \qquad (4.12a)$$

$$\text{s.t.} \quad (3.1) - (3.7) \qquad (4.12b)$$

For a P credit of less than 2 USD/lb P, the optimization model does not find it profitable to process waste and recover products (Table 7 and Table 8). When the credit increases to 20 USD/lb P, the model finds it more profitable to process all waste and recover nutrient cakes. Even though the nutrient cakes have a lower P concentration and a lower product value (compared to struvite), the associated production costs are also lower. Also, cake recovery technologies (filter and coagulation-flocculation) are much simpler to deploy than the struvite recovery technologies.

A P credit of 5 USD/lb P produces profit but a low ROI of 3.5%. Increasing the P credit to 10 USD/kg P increases the ROI by an order of magnitude (to 35.7%), bringing down the payback period to less than 3 yrs. This sudden jump in ROI reveals that there exists a highly non-linear relationship between the P credit and the ROI. Further increasing the P credit to 15 USD/lb P and 20 USD/lb P brings down the payback period to less than 2 years. The ROI for 15 USD/lb P, however, is higher than the ROI for 20 USD/lb P because our objective function is to maximize the profit, which is higher in the case of USD 20/lb P while associated production costs are higher for 20 USD/lb P, thus reducing the corresponding ROI.

4.4 Combining Incentives from RECs, RINs, and Phosphorus Credits

We now introduce incentives from electricity recovery (RECs), transportation fuel production (RINs), and nutrient recovery (P credits) simultaneously. We analyze the incentive values offered at present. A REC value of 2 USD/MWh, RIN value of 2 USD/gal, and P credit of 10.10 USD/lb P (i.e. 22.04 USD/kg P) are considered. The objective for this analysis is to maximize the overall profit including the revenues from all the incentives:

$$\max \quad \varphi_r + \varphi_{r,REC} + \varphi_{r,RIN} + \varphi_{r,P} - \varphi_I - \varphi_O - \varphi_t \qquad (4.13a)$$

$$\text{s.t.} \quad (3.1) - (3.7) \qquad (4.13b)$$

In Table 9, we present the recovered products when all incentives are realized and the overall profit is maximized. We observe that the best strategy is to combine biogas upgrading and nutrient recovery. In particular, the model finds that the optimal strategy is to recover cake$_1$, cake$_3$, and liquefied biomethane using technologies t_{12}, t_{18}, and t_{36}. The technologies t_{12} and t_{36} are the same, just differing in production scales. These technologies recover cake$_1$ and liquefied biomethane. Technology t_{18} recovers cake$_3$ and liquefied biomethane.

The model also installs a total of 31 technologies. Notably, all of these selected technologies produce liquefied biomethane and recover nutrient-rich cakes. This helps realize RIN and P credits simultaneously. Also, since AD is the common processing step for biogas upgrading and nutrient recovery, the production cost for LBM and nutrient cakes is brought down as the cost of AD gets split between the two products. The ROI for this solution is 20.9%, resulting in an attractive payback period of less than 5 years (Table 10). We highlight that these favorable results are obtained with current policy incentives.

The left diagrams in Figure 4 showcase the technologies selected by the model and the amount of products recovered annually. The diagram on the right indicates the locations where these technologies are installed and the optimal transportation routes between them. 59% of the total waste generated in the system is moved across the state ($\varphi_{t,\mathrm{waste}}$). The yellow rings indicate the siting of cake$_1$ and LBM recovery technologies (t_{12} and t_{36}), while the green ring indicates the siting of cake$_3$ and LBM recovery technology (t_{18}). The blue arrows indicate the flow of manure between dairy farms.

5 Conclusions

We present a multiproduct supply chain framework to analyze different technology deployment and incentive strategies for the conversion of post-livestock organic material to value-added products. The management of dairy waste in the State of Wisconsin was employed as the case study. We have found that sustainable waste management would not be an economically viable option unless incentives are provided. It was found that, with current RIN incentives, the deployment of liquefied biomethane production facilities is an economically viable option but the payback period is low (19 yrs). Nutrient credits can make

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the recovery of nutrient-rich products profitable with an attractive payback period (3 yrs), but this result is based on the consideration that the value of nutrient credits for the recovered nutrient-rich products will be the same as that being currently offered for the avoided P discharge to the water bodies. In the case of RECs, current incentives do not make electricity recovery economically viable. When all incentives are simultaneously considered, it is found that combined technologies to produce liquefied biomethane and nutrient cakes can achieve payback periods of less than 5 years. These conclusions are based on data available in the literature for the treatment of dairy waste which can fluctuate significantly. As part of future work, we will use stochastic programming techniques to account for uncertainty in a systematic manner. We are also interested in developing a market modeling framework to derive prices for products.

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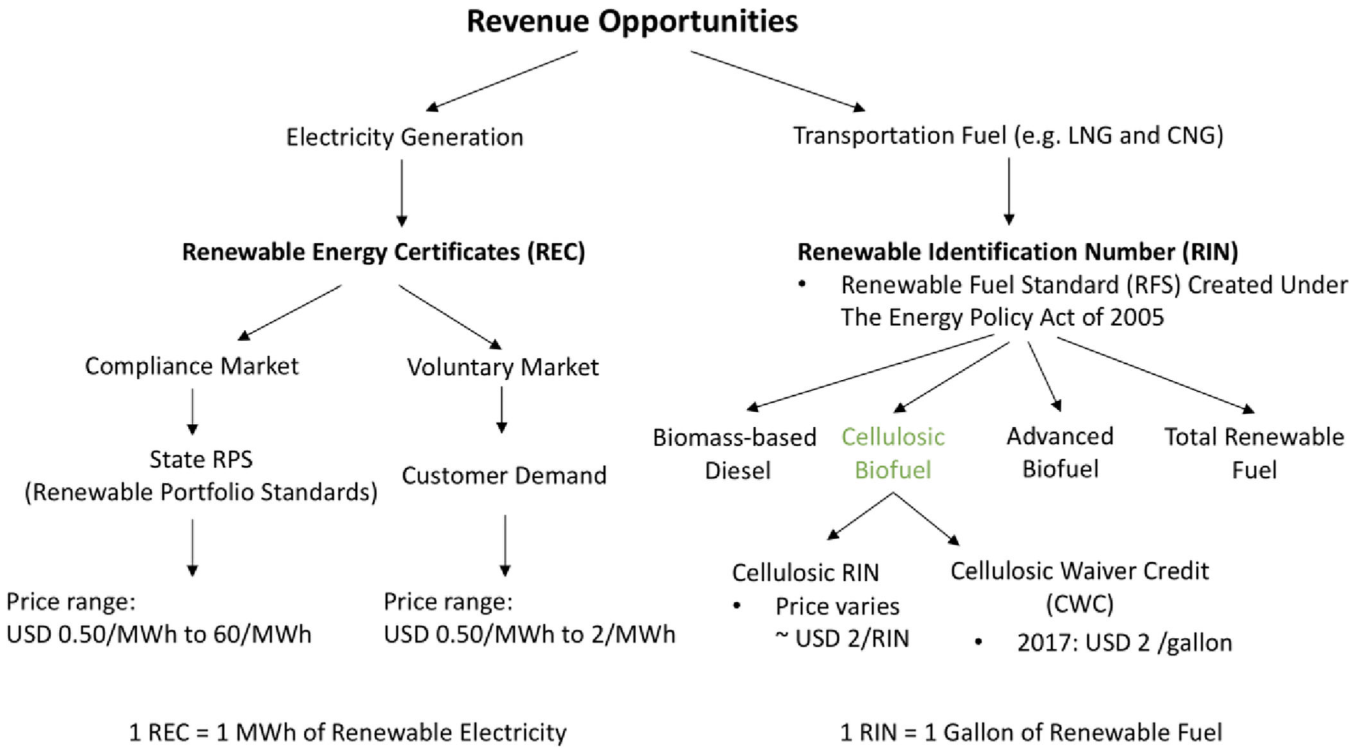

Figure 1:
Economic incentives associated with renewable energy and fuel recovery from livestock waste

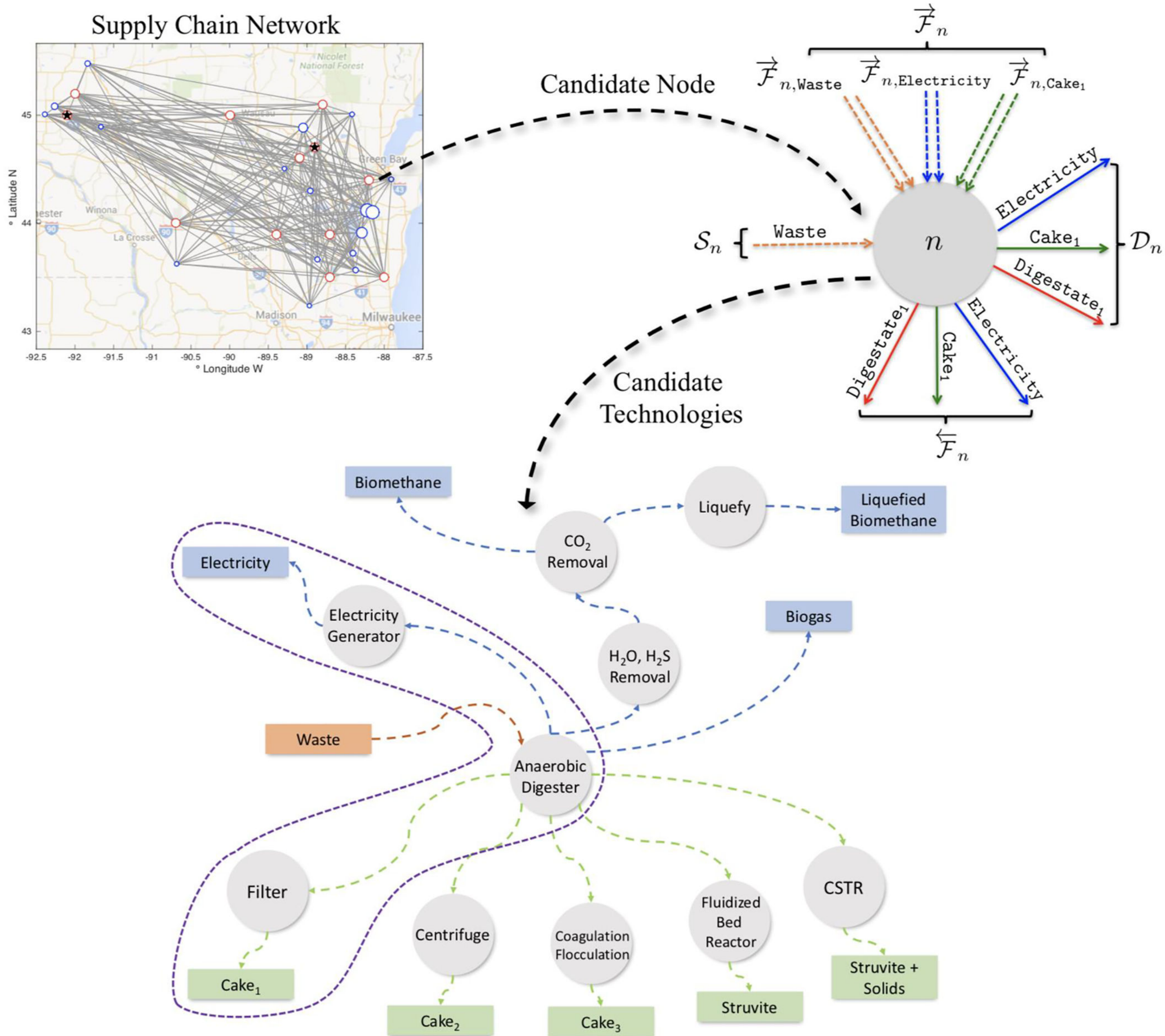

Figure 2:

Sketch of input and output flow sets into a candidate node $n \in \mathcal{N}$ (in a supply chain network) for products P ={Waste, Electricity, Cake_1, Digestate_1}. The multiproduct model selects the technology from a set of candidate technologies ($\mathcal{T}$) illustrated in the graph.

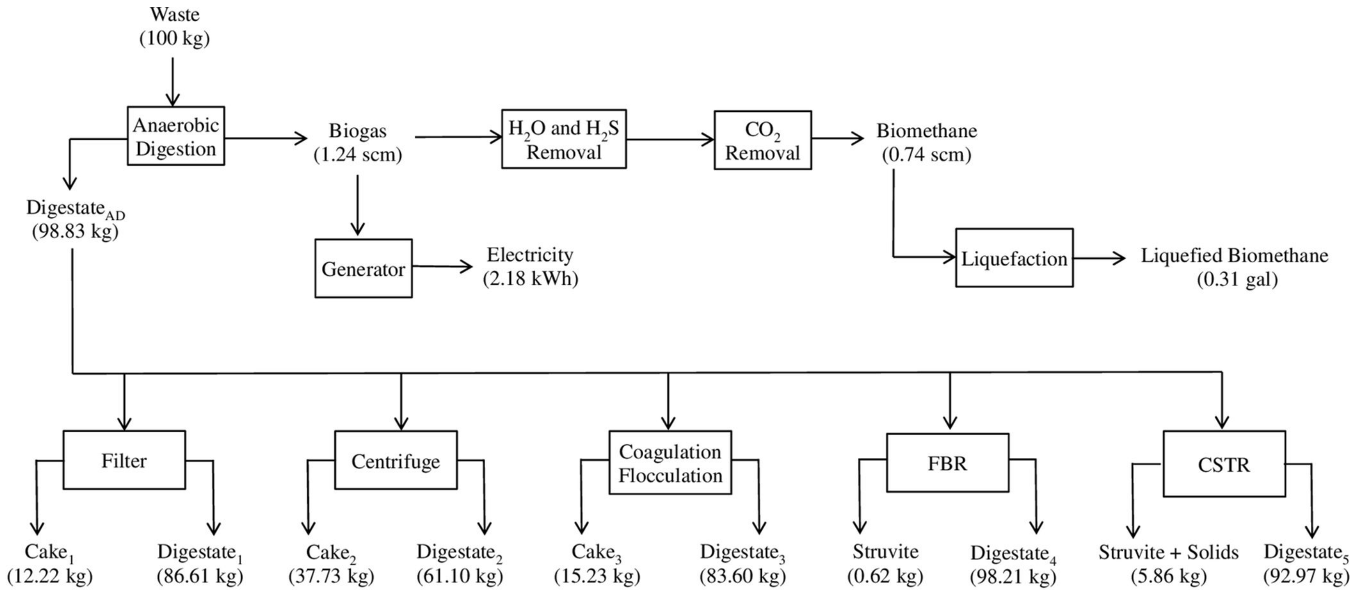

Figure 3:
Product slate with corresponding product yields for an input of 100 kg of waste

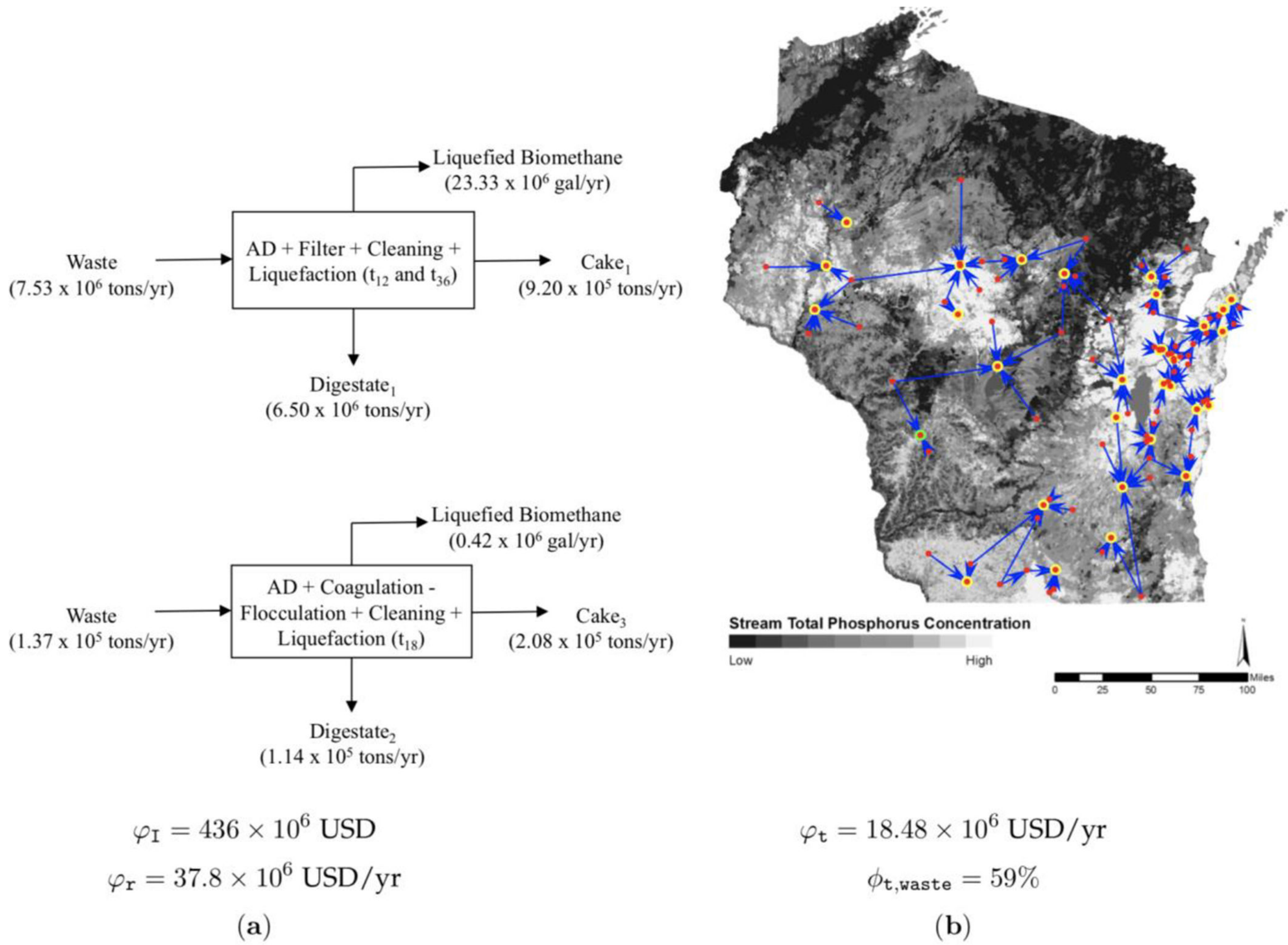

Figure 4:

Optimal solution when all incentives are realized simultaneously. (a) Block diagram representing the technologies sited. (b) Optimal system layouts. The red dots indicate the location of CAFOs and the blue lines indicate the flow of waste. Yellow rings denote the locations of technologies t_{12} and t_{36}. Green ring indicates the siting of technology t_{18}. (The map of the State of Wisconsin has been adapted from [47])

Table 1:

Waste composition (excreted manure after dilution with wash water)

Component	Kg	%
Water	159.43	93.00
Phosphorus (P)	0.13	0.08
Nitrogen (N)	0.32	0.19
Potassium (K)	0.32	0.32
Carbon (C)	6.26	3.65
Miscellaneous	4.67	2.72
Total	171	100

Table 2:

Market value (calculated in Section 4.1) for different products with the associated phosphorus content, phosphorus efficiency, and carbon efficiency

Products	Product Name	Market Value	Units	Phosphorus Content (% wt)	Phosphorus Efficiency (%)	Carbon Efficiency (%)
*p*1	Waste	0	USD/ton	0.08	-	-
*p*2	Electricity	0.04	USD/kWh	0	0	0
*p*3	Biogas	0.048	USD/scm	0	0	15
*p*4	Biomethane	0.15	USD/scm	0	0	10
*p*5	Liq. Biomethane	1	USD/gal	0	0	10
*p*6	Cake1	15	USD/ton	0.57	86	85
*p*7	Cake2	4.9	USD/ton	0.21	95	85
*p*8	Cake3	12.5	USD/ton	0.52	99	85
*p*9	Struvite	800	USD/ton	12.57	90	85
*p*10	Struvite + Solids	77.3	USD/ton	1.22	90	85
*p*11	DigestateAD	0	USD/ton	0.08	-	-
*p*12	Digestate1	0	USD/ton	0.012	-	-
*p*13	Digestate2	0	USD/ton	0.002	-	-
*p*14	Digestate3	0	USD/ton	0.001	-	-
*p*15	Digestate4	0	USD/ton	0.002	-	-
*p*16	Digestate5	0	USD/ton	0.01	-	-

Table 3:

List of candidate technologies with corresponding investment and operation cost

		Capacity = 3.75×10^5 (kg/day) (5,000 AU)			Capacity = 7.49×10^5 (kg/day) (10,000 AU)		
Sr. No.	**Technology**	**Tech. No.**	**Investment Cost (USD)**	**Operation Cost (USD/yr)**	**Tech. No.**	**Investment Cost (USD)**	**Operation Cost (USD/yr)**
1	AD	t_1	$2.69 \times 1O^6$	6.45×10^4	t_{25}	5.01×10^6	1.20×10^5
2	AD + Generator	t_2	$6.46 \times 1O^6$	3.23×10^5	t_{26}	1.02×10^7	5.10×10^5
3	AD + Cleaning	t_3	$4.51 \times 1O^6$	2.12×10^5	t_{27}	7.89×10^6	3.53×10^5
4	AD + Cleaning + Liquefaction	t_4	9.05×10^6	2.79×10^5	t_{28}	1.51×10^7	4.59×10^5
5	AD + Filter	t_5	2.70×10^6	1.34×10^6	t_{29}	5.04×10^6	2.14×10^6
6	AD + Centrifuge	t_6	4.09×10^6	2.04×10^6	t_{30}	7.24×10^6	3.26×10^6
7	AD + Coag-Floc	t_7	6.46×10^6	1.74×10^6	t_{31}	1.10×10^7	2.79×10^6
8	AD + FBR	t_8	5.33×10^6	3.06×10^6	t_{32}	9.21×10^6	4.87×10^6
9	AD + CSTR	t_9	5.90×10^6	3.26×10^6	t_{33}	1.01×10^7	5.20×10^6
10	AD + Filter + Generator	t_{10}	6.47×10^6	1.59×10^6	t_{34}	1.02×10^7	2.53×10^6
11	AD + Filter + Cleaning	t_{11}	4.52×10^6	1.48×10^6	t_{35}	7.91×10^6	2.37×10^6
12	AD + Filter + Cleaning + Liquefaction	t_{12}	9.06×10^6	1.55×10^6	t_{36}	1.51×10^7	2.48×10^6
13	AD + Centrifuge + Generator	t_{13}	7.86×10^6	2.30×10^6	t_{37}	1.24×10^7	3.65×10^6
14	AD + Centrifuge + Cleaning	t_{14}	5.91×10^6	2.19×10^6	t_{38}	1.01×10^7	3.49×10^6
15	AD + Centrifuge + Cleaning + Liquefaction	t_{15}	1.05×10^7	2.25×10^6	t_{39}	1.73×10^7	3.59×10^6
16	AD + Coag. Floe. + Generator	t_{16}	1.02×10^7	2.00×10^6	t_{40}	1.62×10^7	3.18×10^6
17	AD + Coag. Floe. + Cleaning	t_{17}	8.28×10^6	1.89×10^6	t_{41}	1.39×10^7	3.02×10^6
18	AD + Coag. Floe. + Cleaning + Liquefaction	t_{18}	1.28×10^7	1.96×10^6	t_{42}	2.10×10^7	3.12×10^6
19	AD + FBR + Generator	t_{19}	9.10×10^6	3.31×10^6	t_{43}	1.44×10^7	5.26×10^6
20	AD + FBR + Cleaning	t_{20}	7.15×10^6	3.20×10^6	t_{44}	1.21×10^7	5.10×10^6
21	AD + FBR + Cleaning + Liquefaction	t_{21}	1.17×10^7	3.27×10^6	t_{45}	1.93×10^7	5.21×10^6
22	AD + CSTR + Generator	t_{22}	9.68×10^6	3.52×10^6	t_{46}	1.53×10^7	5.59×10^6
23	AD + CSTR + Cleaning	t_{23}	7.73×10^6	3.41×10^6	t_{47}	1.30×10^7	5.43×10^6

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		Capacity = 3.75×10^{5} (kg/day) (5,000 AU)			Capacity = 7.49×10^{5} (kg/day) (10,000 AU)		
Sr. No.	**Technology**	**Tech. No.**	**Investment Cost (USD)**	**Operation Cost (USD/yr)**	**Tech. No.**	**Investment Cost (USD)**	**Operation Cost (USD/yr)**
24	AD + CSTR + Cleaning + Liquefaction	t_{24}	1.23×10^{7}	$3.48 \times 1O^{6}$	t_{48}	2.02×10^{7}	5.54×10^{6}

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Table 4:

Product value analysis. (Note that the break-even values reported here are for each product considered in isolation)

Product	**Market Value (from Literature)**	$\varphi_I + \varphi_o$	$\varphi_I + \varphi_o$	**Break-even value (from model)**	**Units**
		(5,000 AU, from data)	**(10,000 AU, from data)**		
Electricity	0.04	0.22	0.11	0.18	USD/kWh
Biogas	0.048	0.12	0.11	0.15	USD/scm
Biomethane	0.15	0.24	0.22	0.40	USD/scm
Liq. Biomethane	1.00	1.26	0.86	1.5	USD/gal
Cakel	15.0	64	60	70	USD/ton
Cake2	4.9	36	31	35	USD/ton
Cake3	12.5	80	71	78	USD/ton
Struvite	800	3457	2930	3300	USD/ton
Struvite + Solids	77.3	395	333	350	USD/ton

Table 5:

Economics of Renewable Energy Credit (REC) analysis

REC Value	**Electricity Recovered**	**WI Electricity Share (%)**	**Total.**	$\varphi_{p,waste}$	φ_I	φ_o	φ_t	$\varphi_{r,electricity}$	$\varphi_{r,REC}$	**ROI**	**Payback Period**
(USD/ MWh)	**(MVVh/yr)**		**Tech.**	**(%)**	**(USD)**	**(USD/yr)**	**(USD/yr)**	**(USD/yr)**	**(USD/yr)**	**(%)**	**(yrs)**
≤100	0	0	0	0	0	0	0	0	0	0	NA
200	8.35×10^4	0.13	17	49.9	1.51×10^8	7.55×10^6	2.04×10^6	3.34×10^6	1.67×10^7	1.92	52
500	1–65 × 10^5	0.25	43	98.5	3.38×10^8	1.69×10^7	9.69 × 10fi	6.59 × 10°	8.24×10^7	13.48	7
800	1.67×10^5	0.25	43	99.8	3.15×10^8	1.73×10^7	1.03×10^7	fi.68 × 1(1®	1.34 × 10s	27.64	4
1000	1.67×10^5	0.25	44	100	3.48×10^8	1.74×10^7	1.06×10^7	13.69 × in^6	1.67×10^8	36.96	3

Table 6:

Economics of Renewable Identification Number (RIN) Analysis

RIN Value	LBM Recovered	Total Tech. Sited	$\varphi_{p,\,waste}$	φ_I	φ_o	φ_t	$\varphi_{r,LBM}$	φ_{RIN}	ROI	Payback Period (yrs)
(USD/ gal)	(MWh/yr)		(%)	(USD)	(USD/yr)	(USD/yr)	(USD/yr)	(USD/yr)	(%)	
0.5	2.54×10^6	3	10.69	4.53×10^7	1.38×10^6	1.99×10^4	2.54×10^6	1.27×10^6	0.34	296
1	1.31×10^7	20	55.25	2.48×10^8	7.56×10^6	2.34×10^6	1.31×10^7	1.31×10^7	1.62	62
1.5	1.86×10^7	29	78.41	3.53×10^8	1.08×10^7	5.88×10^6	1.86×10^7	2.80×10^7	3.48	29
2	2.17×10^7	37	91.32	4.26×10^8	1.30×10^7	8.55×10^6	2.17×10^7	4.34×10^7	5.24	19
2.5	4.50×10^8	39	96.22	4.50×10^8	1.38×10^7	1.04×10^7	2.29×10^7	5.72×10^7	7.45	13
3	2.30×10^7	39	96.69	4.50×10^8	1.38×10^7	1.09×10^7	2.30×10^7	6.90×10^7	9.98	10

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Table 7:

Products recovered for varying phosphorus credits

Sr. No.	P Credit (USD/lb P)	$Cake_1$ Recovered (tonne/yr)	$Cake_3$ Recovered (tonne/yr)	Biogas Recovered (million scm/yr)	Waste Processed (%)
1	≤ 2	0	0	0	0
2	5	4.02×10^5	0	40.69	43
3	10	9.20×10^5	0	93.25	98
4	15	8.61×10^5	8.33×10^4	94.27	99
5	20	L.84 × 10^5	9.38×10^6	94.94	100

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Table 8:

Economics of phosphorus credits

Sr. No.	Total. Tech.	φ_I (USD)	φ_O (USD/yr)	φ_t (USD/yr)	$\varphi_{r,products}$ (USD/yr)	$\varphi_{r,pcredit}$ (USD/yr)	ROI (%)	Payback Period (yrs)
1	0	0	0	0	0	0	0	N/A
2	12	6.05×10^7	2.57×10^7	2.31×10^6	7.96×10^6	2.52×10^7	3.5	28.4
3	33	1.41×10^8	6.18×10^7	1.46×10^7	1.82×10^7	1.15×10^8	35.7	2.8
4	32	1.54×10^8	6.34×10^7	1.62×10^7	1.85×10^7	1.77×10^8	69.9	1.4
5	33	2.78×10^8	7.73×10^7	1.77×10^7	1.90×10^7	2.Cl × 10^8	61.6	1.6

Table 9:

Products recovered when all incentives are realized and profit is maximized

REC	RIN	P Credit	$\varphi_{r, cake_1}$	$\varphi_{r, cake_3}$	$\varphi_{r,LBM}$	$\varphi_{p, waste}$
(USD/MWh)	(USD/gal)	(USD/lb P)	(tons/yr)	(tons/yr)	(tons/yr)	(%)
2	2	10	9.20×10^5	2.08×10^4	23.74	100

Table 10:

Economics for analysis with simultaneous incentives

Total. Tech,	φ_I	φ_O	φ_t	$\varphi_{r,\ products}$	$\varphi_{r,\ REC}$	$\varphi_{r,\ RIN}$	$\varphi_{r,\ pcredit}$	ROI	Payback Period
	(USD)	(USD/yr)	(USD/yr)	(USD/yr)	(USD/yr)	(USD/yr)	(USD/yr)	(%)	(yrs)
31	4.36×10^8	7.17×10^7	1.84×10^7	$3{,}78 \times 10^7$	0	4.75×10^7	1.18×10^s	20.9	4.8