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An evaluation of anaerobic co-digestion implementation on New York State dairy farms using an environmental and economic life-cycle framework

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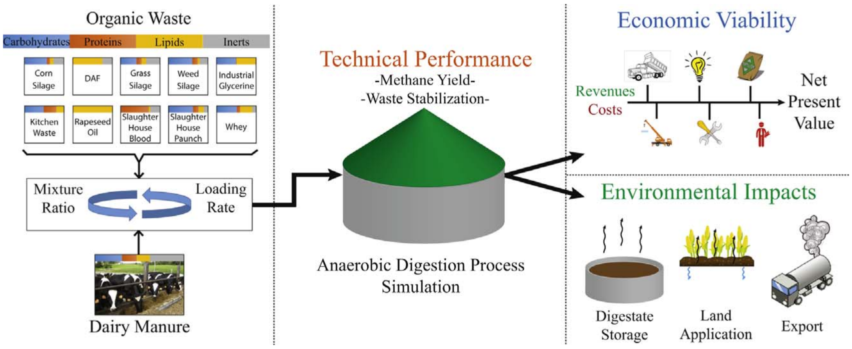
HIGHLIGHTS

- The life-cycle performance of 10 co-digestion substrates were compared.
- AD performance is sensitive to co-substrate properties and management strategy.
- High loading rates are economically favorable yet increase farm-level emissions.
- Co-digestion lowers total environmental impacts compared to manure-only digestion.
- Economic profitability of the AD system is driven primarily by gate-fee revenue.

GRAPHICAL ABSTRACT



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ABSTRACT

Anaerobic digestion systems on dairy farms in New York State rely on gate-fee revenues from co-digestion to ensure economic viability. Yet, because gate fees are paid on a volumetric (or weight) basis, farmers have been compelled to accept large waste volumes. When these wastes are co-digested at rates exceeding the design capacity of the digester, potentially significant technical, environmental, and economic consequences may arise. To better understand these trade-offs, we performed a combined environmental life-cycle and economic assessment with uncertainty analysis. We used the Anaerobic Digestion Model #1 to simulate the co-digestion process for 10 potential co-substrates that were hypothetically mixed with dairy manure throughout a range of loading rates. These simulation results demonstrated the need to include a robust anaerobic digestion model to capture complex process dynamics and loading limits. Results also showed that while higher loading rates were more economically favorable, they caused considerable reductions in the degree of waste stabilization during the digestion process, which dramatically increased downstream methane emissions (*e.g.,* > 450%) on the farm compared to manure-only digestion. Regardless, most co-digestion scenarios led to a net reduction in total life-cycle emissions compared to manure only and not digesting the co-substrate due mainly to greater electric power

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Abbreviations: AD, anaerobic digestion; ADM1, anaerobic digestion model #1; CHP, combined heat and power; COD, chemical oxygen demand; DAF, dissolved-air flotation sludge; GHG, greenhouse gas; GWP, global warming potential; HRT, hydraulic retention time; LCA, life-cycle assessment; LCI, life-cycle inventory; N, nitrogen; P, phosphorus; K, potassium; NPV, net present value; NYS, New York State; SCOD, soluble chemical oxygen demand; SMY, specific methane yield; TCOD, total chemical oxygen demand

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production and synthetic fertilizer replacement. Economically, gate-fee revenue was the most important contributor to profitability, substantially outweighing the revenue from electric power production, while also compensating for the increased handling costs of the added waste volume. Ultimately, the model clearly demonstrated the important environmental and economic implications arising from current anaerobic digestion implementation practices and policy in New York State. In addition, the model highlighted key stages in the system life-cycle, which was used to instruct and recommend immediately actionable policy changes.

1. Introduction

Livestock operating systems, such as beef and milk producing farms, are inherently resource intensive and environmentally detrimental; yet, demand for beef and milk products continues to grow globally [1]. Through anaerobic digestion (AD), some of the carbon that is present in livestock manure and other agricultural residues is recaptured as methane, which may then be used in a combined heat and power (CHP) cycle. As an end-use technology, CHP is reliable and versatile and with short-term storage, can produce base-load power and heat. Besides energy production, there are additional opportunities to improve waste stabilization and nutrient emissions to further mitigate environmental impacts compared to conventional livestock operations [2]. For instance, the macronutrients (nitrogen [N], phosphorus [P], and potassium [K]) are partly mineralized and mostly conserved during the AD process, and thus the digestate may serve as a substitute for synthetic fertilizers [3]. Also, the use of digestate rather than raw manure often facilitates nutrient recovery, using technologies such as: membrane separation, ammonia stripping, and struvite precipitation [4].

Even without nutrient recovery, life-cycle assessment (LCA) studies predict considerable environmental impact reductions when AD is used in place of conventional manure management [5,6]. The majority of the environmental impact reductions in these studies came from the displacement of fossil-fuel derived electric power or heat. In the U.S., AD from livestock operating systems alone has the potential to generate an estimated 5.5% of U.S. electric power [2]. Co-digestion of dairy manure with other organic waste streams, such as food waste (40 million tons annually [7]), would considerably increase AD electric power generation potential and further reduce environmental impacts. Due to these perceived benefits, many federal and state governmental agencies are actively subsidizing AD implementation on farms *via* capital cost sharing grants and compensation for electric power production. Despite these financial incentives, however, high capital and operating costs still represent a major barrier toward achieving economic viability [2,8].

Consequently, farmers are increasingly relying on co-digestion of externally sourced organic wastes to provide additional revenue in the form of gate fees. In fact, a marked increase in co-digestion implementation has been observed during the last 10 years, with 98 of the 260 farm-based AD operating systems in the U.S. now applying co-digestion [5]. However, because gate fees are paid on a per volume (or weight) basis (*e.g.,* \$60–100 m^{-3}) [9], farmers are incentivized to maximize the loading rate of these co-substrates. This often results in system overloading, which decreases digester stability and performance (*i.e.*, specific methane yields and waste stabilization). Moreover, the digestate from an overloaded AD system may induce greater residual methane and nutrient emissions downstream of the digester, especially when open digestate storage is employed [10]. Finally, the additional volume and nutrients embedded in the digestate may incur greater downstream-handling costs; for example, from increased storage infrastructure, transport distances, and digestate export [11]. These environmental and economic considerations are important given the versatility of the AD process, which permits the use of compositionally diverse feedstock across a relatively wide range in loading rates [12].

To our knowledge, the environmental and economic life-cycle consequences resulting from feedstock selection combined with a specific AD management strategy have not been systematically evaluated. Moreover, none of the existing life-cycle studies have included a robust AD process-based model capable of capturing the potentially important dynamic effects or process limits arising from organic overloading or substrate-related inhibition. Rather, these studies select a single substrate mixture and then assign a static value for methane yield, nutrient concentrations, and digestate composition. Using a simplified approach is acceptable for rough estimates of AD process performance at conservative loading rates. However, this approach is less appropriate for high co-digestion mixture ratios and loading rates, which is the way most farm-based AD systems are being operated in the U.S. Therefore, the inclusion of a more robust model at the AD process stage may prove to be important for quantifying final life-cycle outcomes.

A sufficiently robust AD process model is the Anaerobic Digestion Model #1 (ADM1). ADM1 is a dynamic anaerobic digestion modeling tool developed by the International Water Association Anaerobic Digestion Modelling Task Group. This structured model combines differential and algebraic equations to simulate the physicochemical (acid-base reactions, liquid-gas transfer) and biochemical kinetic processes (biomass growth and decay, disintegration, hydrolysis, acidogenesis, acetogenesis, and methanogenesis), and the various process inhibitions associated with AD [13]. Moreover, the model allows detailed feedstock characterization and dynamic flow-rate inputs to predict methane production, biogas composition (*i.e.,* CH_4, CO_2, and H_2), N mineralization, and digestate composition, amongst other parameters [13]. The ADM1 model has been validated by multiple research groups for a wide range of feedstock and operating conditions [13].

Here, our objective was to systematically evaluate the technical, environmental, and economic consequences associated with co-digestion feedstock selection and management strategy in NYS for a 1000-cow dairy farm. Furthermore, because the operating choices will alter the performance of the AD system, we sought to determine whether it was necessary, from the standpoint of causing significant changes in life-cycle outcomes, to more accurately estimate AD performance using a robust AD process-based model rather single-value estimates. To address the high degree of uncertainty associated with emission factor estimates in agricultural systems, we included an uncertainty analysis to further qualify the significance of our model results. We hypothesized that the three fundamental parameters: (1) feedstock selection; (2) co-digestion loading rate; and (3) changes in AD process performance would significantly affect both the environmental and economic life-cycle outcomes of the AD system. In addition, we anticipated that by combining the technical, environmental, and economic aspects of the AD system, this model would be able to identify key life-cycle stages, and thereby help guide future co-digestion implementation practices and policy.

2. Methods

2.1. Model description

Dairy manure served as the basal substrate for anaerobic digestion in all model scenarios, and when digested alone, represented the base case to which all co-digestion scenarios were compared. The co-digestion scenarios involved 10 unique co-substrates, which were separately mixed with manure at incremented loading rates spanning the technical range of the AD process. The co-substrates were selected to ensure variation in these three key characteristics: (1) organic composition; (2)