Life cycle analysis of renewable natural gas and lactic acid production from waste feedstocks

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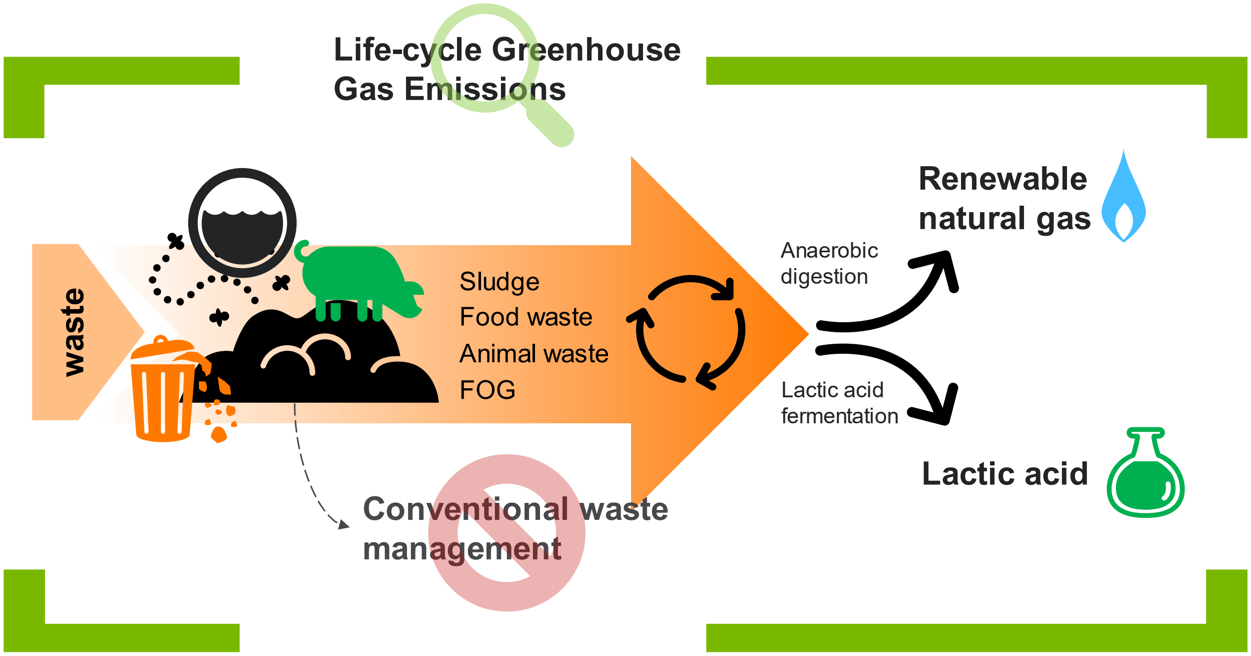
Abstract

Producing fuels and chemicals from waste is considered economically favorable, due to low feedstock cost, and environmentally favorable, due to avoided emissions from conventional waste management practices. In this study, we evaluate the life cycle greenhouse gas (GHG) emission reduction benefits of renewable natural gas (RNG) and lactic acid (LA) production from four types of wet waste feedstocks (wastewater sludge, food waste, swine manure, and fats, oil, and grease [FOG]) via anaerobic digestion (AD) and LA fermentation, respectively. RNG can be used as an alternative to fossil natural gas, while LA from waste feedstocks can displace conventional LA production pathways (mainly from corn via fermentation). Providing comprehensive life cycle GHG emissions of the combinations of waste feedstocks and products through different routes helps identify the GHG hotspots and show where emissions savings come from. The results show that the carbon intensities (CIs) of waste-derived RNG and LA are much lower than those of their counterparts. We estimated the life cycle GHG emissions for RNG to be between -146 and 27 g carbon dioxide equivalent (CO_2e)/MJ, much lower than the CI of fossil fuels. Waste-derived LA pathways also show substantially lower CIs, ranging from -4.2 to -1.4 kgCO_2e/kg LA, compared to the CIs of LA from corn and corn stover (1.2 and 0.3 kgCO_2e/kg LA, respectively). We will also discuss that the low CIs of waste-derived products can come from low yields leading to high emission credits. Thus, life cycle analysis results presented per weight of treated waste can be used to support decisions about which waste feedstocks and products are to be used for sustainable waste valorization. In addition, we found that monetary emission reduction credits can play an important role in driving waste valorization.

Keywords: renewable natural gas, lactic acid, waste, life cycle analysis, greenhouse gas emissions, anaerobic digestion, lactic acid fermentation, carbon intensity

Graphical Abstract



Highlights:

- Renewable natural gas and lactic acid can be produced from organic waste materials
- Conducted LCA to quantify the environmental benefits of waste-derived products
- Producing fuels/chemicals from waste can reduce GHG emissions
- Quantified potential economic benefits led by GHG emission reductions
- Economic benefits by GHG emission reductions can drive waste valorization

1 Introduction

Livestock and poultry in the U.S. generate over a billion tons of manure each year (U.S. EPA, 2013) or 38 million metric tons (MMT) of dry material (Skaggs et al., 2017). Waste management systems handle an additional 14 dry MMT of food waste; another 13 dry MMT of wastewater sludge is produced by U.S. wastewater treatment facilities annually; and fats, oil, and grease (FOG) generation is estimated at 5.4 MMT (Skaggs et al., 2017). These organic waste materials generally generate significant greenhouse gas (GHG) emissions in the waste management process. In 2017, landfills in the U.S. emitted 108 MMT carbon dioxide equivalent (CO_2e) of methane (CH_4), which is 16.4% of the U.S. total CH_4 emissions and 1.7% of U.S. total GHG emissions (U.S. EPA, 2019). Manure management generates 80.4 MMT CO_2e each year, and wastewater treatment plants (WWTPs) and composting of organic waste produce 14.2 and 2.2 MMT CO_2e, 2.2% and 0.3 % of total U.S. CH_4 emissions, respectively (U.S. EPA, 2019).

However, these organic materials have the potential to serve as feedstocks for valuable products and/or fuels instead. Using waste feedstocks for beneficial uses such as generating energy or producing chemical products can provide economic benefits through reducing product feedstock costs, which can even be negative due to avoided costs of waste management (Badgett et al., 2019). Energy and chemical products provide additional revenue streams for waste management facilities. Furthermore, as conventional waste management practices result in environmental impacts, including GHG emissions and soil and water pollution, diverting waste to valuable products can help avoid impacts from waste management while potentially offsetting the impacts of producing those products in other ways.

Anaerobic digestion (AD), a mature and cost-effective waste management technology for treating wet organic wastes (Lee et al., 2016a; Rajendran and Murthy, 2019), can be used for renewable natural gas (RNG) production (Shen et al., 2015). In the AD process, microbes digest organic materials, decreasing the volume of waste requiring disposal, generating biogas, and creating stable digestate (Kuo and Dow, 2017; Lee et al., 2016a; NREL, 2013; Tsachidou et al., 2019; U.S. DOE, 2017; Weiland, 2010). AD is used widely in WWTPs for the treatment of sludge (Shen et al., 2015) and is growing in popularity as a method of energy production from other organic wet wastes such as food waste, animal waste, and FOG (De Vries et al., 2012; U.S. EPA, 2018; Long et al., 2012; Tong et al., 2019; Xu et al., 2018). Biogas (a mixture of CH_4 and CO_2) from the AD process can be upgraded to pipeline quality RNG with high CH_4 concentration, comparable to fossil natural gas (NG), by stripping undesirable components. RNG can displace fossil NG, providing the benefit of reductions in life cycle GHG emissions (Cuimei et al., 2018; NREL, 2013; Weiland, 2010).

Recent research efforts make it possible to convert wet waste feedstocks into high-value chemical products such as lactic acid (LA) through LA fermentation (also known as arrested AD processes or arrested methanogenesis) (Bhatt et al., 2020). LA is used in the pharmaceutical, cosmetic, chemical, and food industries (Eş et al., 2018). Since LA is used as a precursor for polylactic acid (PLA), a biodegradable plastic that has been receiving growing attention, it is expected that the demand for LA will expand in the future (Bhatt et al., 2020). Currently, LA is mostly produced from biomass feedstocks such as corn or corn stover through fermentation processes (Adom and Dunn, 2017; Dunn et al., 2015; Komesu et al., 2017), which can be displaced by waste-derived LA produced via LA fermentation.

Life cycle analysis (LCA) is used to understand the energy and environmental benefits and potential tradeoffs of various pathways and allows the environmental impact of different pathways to be compared. There have been many LCA studies on AD of waste, mainly comparing traditional waste management methods to see the environmental risks and benefits (Cao and Pawłowski, 2013; De Vries et al., 2012;

Edwards et al., 2018, 2017; Li et al., 2017; Mills et al., 2014; Shen et al., 2015; Tong et al., 2019). For example, LCA studies on sludge AD show a reduction in GHG emissions compared to other sludge management practices (Lee et al., 2016a; Li et al., 2017; Mills et al., 2014). AD of food waste also shows a reduced global warming potential (GWP) compared to landfilling (Edwards et al., 2018). Some studies evaluate the impact of co-digesting two or more waste streams to increase the yield, which shows the potential benefits of maximizing existing AD systems while increasing productivity (De Vries et al., 2012; Edwards et al., 2018; Long et al., 2012; Tong et al., 2019). Most studies on LCA of LA have focused on evaluating the conventional LA production pathways via fermentation processes, mainly from corn and corn stover (Adom and Dunn, 2017; Daful et al., 2016; Dunn et al., 2015; Khoo et al., 2016). Some studies have presented the feasibility of using waste feedstocks (e.g., waste sugarcane bagasse and food waste) for LA production via fermentation (Adsul et al., 2007; Kim et al., 2016; Kwan et al., 2018).

While many individual LCA studies quantify the environmental benefits of various waste valorization pathways, there have been no LCA studies that comprehensively compare multiple options from various waste feedstocks. Comparing results across previous studies is fraught with difficulty, due to differences in the goals, system boundaries, and assumptions used in each. Providing results across pathways on a consistent basis allows for a fair comparison, so that the impact of choosing different feedstocks/products combinations can be compared for an informed decision. In addition, the concept of LA fermentation for LA production is new; there have been no LCA studies so far providing the LCA results of waste-derived LA production via LA fermentation.

The objective of this study is to present the life cycle GHG emissions of RNG and LA production via AD and LA fermentation, respectively, from four waste feedstocks to understand the tradeoffs of these pathways and relative environmental benefits. This study specifically discusses the impact of choosing a combination of the waste feedstock and the conversion technology (and the corresponding product), which enables comparisons with other waste management practices or conventional RNG/LA production pathways. In particular, this is the first LCA of LA production from LA fermentation. This study provides guidance on decision making regarding the waste feedstock to use, the conversion process to employ, and the products to generate to benefit the sustainability of the process. In addition, we discuss the impact of monetary carbon emission reduction credits and potential emission reduction credits with the use of these pathways.

2 Methodology

2.1 System Boundary and Feedstock Characteristics

Figure 1 presents the LCA system boundary of these pathways (cradle-to-gate) and depicts avoided business as usual (BAU) scenarios. For RNG production, biogas (a mixture of CH_4 and CO_2) from AD of wet waste feedstocks is upgraded to RNG to be used as fuel. During the AD process, digestate is generated, which is assumed to be landfilled. Similarly, for LA production, four types of wet waste are used for LA production via LA fermentation, which generates LA rather than biogas by inhibiting CH_4 production.

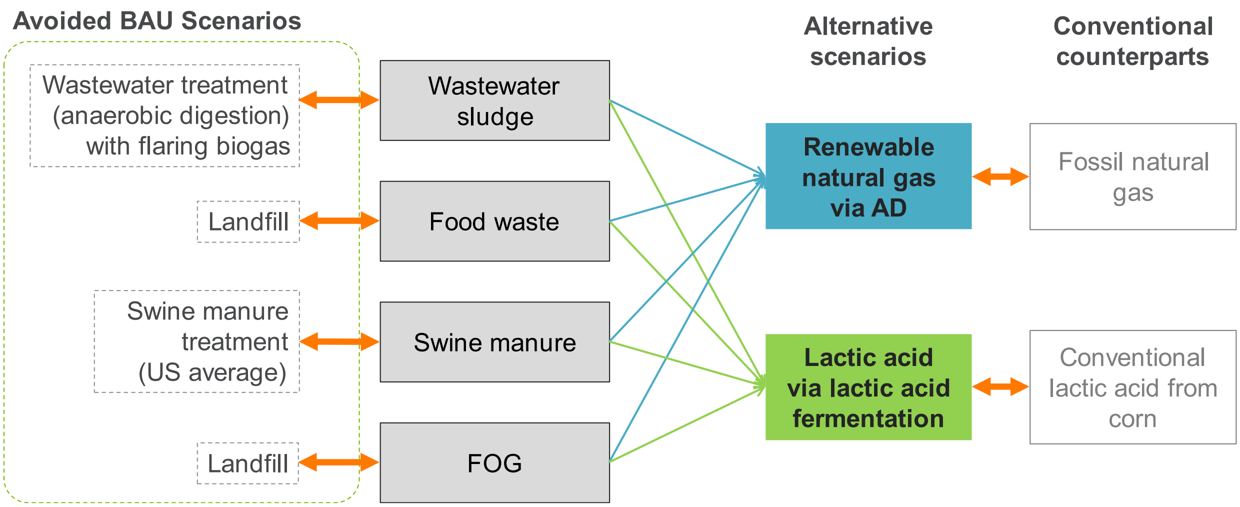


Figure 1. The LCA system boundary of RNG and LA production pathways using sludge, food waste, swine manure, and FOG

The LCA results are presented using two different functional units: We present life cycle GHG emission results 1) per dry kg of waste treated, and 2) per MJ or kg of product. The first functional unit is useful for comparing the LCA results with other waste management practices. When comparing dry kg waste results, RNG/LA production pathways generate products that can could potentially augment the supply of and/or serve as a substitute for their conventional counterparts. Thus, it is assumed that fossil NG production pathways are displaced when RNG is produced from waste. Similarly, we assumed LA produced from wet waste feedstocks displaces conventional LA production from corn. Alternatively, we present LCA results in terms of MJ RNG or kg LA to be compared with those of their counterparts. For example, the carbon intensity (CI) of RNG (gCO_2e/MJ) produced via AD can be compared with other energy products (e.g., the CI of gasoline) to determine how much GHG emission reduction would be achieved per MJ of fuel displacement. Upstream energy and emission burdens are not accounted for in waste feedstock production.

Table 1 shows the wet waste feedstock compositions, carbon and nitrogen contents, and energy densities analyzed in this paper, which are from the studies by Bhatt and Tao (2020) and Bhatt et al. (2020). The feedstock composition and energy density are based on data obtained from several studies (Chartier and Palz, 2012; ECN, 2020; Energy Information Administration, 2007; Long et al., 2012; Martínez et al., 2011; Seiple et al., 2017; Skaggs et al., 2017; Theofanous et al., 2014; Turovskiy and Mathai, 2006; U.S. DOE, 2017; Wang et al., 2014; Xia et al., 2012), while the elemental composition of carbon and nitrogen are calculated. For wastewater sludge, the composition in Table 1 represents typical wastewater sludge, although the composition varies greatly depending on sources, pretreatment technologies and dewatering techniques employed at the facility. Non-fermentable components and ash represent 42% of the dry mass, leaving only 58% fermentable components. For food waste, the composition varies by type (waste during preprocessing, manufacturing, consumption, and distribution) and source (kitchen waste, university cafeterias, restaurants, etc.), with 95% volatile (or fermentable) solids for biological conversion. Like food waste, swine manure is high in carbohydrates, with 60.3% volatile solids. In this study, we consider fat as a primary source of the FOG stream, which is assumed to have 90% moisture, and the dry weight solids have 78% lipids, 7% proteins, and 15% carbohydrates.

Table 1. Feedstock properties of the four waste feedstocks used in this study

Parameters	Sludge	Food Waste	Swine Manure	FOG
Ash	7.5%	5.0%	15%	0%
Lipids	18%	21%	3.8%	78%
Proteins	24%	19%	20%	7.0%
Fermentable carbohydrates	16%	55%	37%	15%
Lignin	0%	0%	21%	0%
Other non-fermentable components (e.g., extractives)	35%	0%	3.5%	0%
Energy density (MJ/dry kg)	21	24	18	41
Moisture content (%)	96%	75%	93%	90%
Carbon (dry wt%)	40%	51%	44%	71%
Nitrogen (dry wt%)	4.3%	3.4%	3.5%	1.2%

In order to present how much carbon in feedstocks ends up in the products, we calculate carbon conversion rate, which is calculated as the ratio between carbon in the product ($C_{product}$; RNG or LA) and carbon in waste feedstocks ($C_{feedstock}$; sludge, food waste, swine manure, and FOG) (Eq. 1).

$$C_{product} / C_{feedstock} \qquad \text{(Eq. 1)}$$

The life cycle impacts are evaluated using the Greenhouse gases Regulated Emissions, and Energy Technologies (GREET®) model (Wang et al., 2020), and emissions during the fuel conversion processes and transportation are estimated as well. We assume that the conversion facilities are located where these waste materials are currently treated, and therefore no additional feedstock transportation is required. All the upstream impacts of energy (fossil natural gas and electricity) and chemical inputs are estimated using the U.S. average default conditions in GREET. We used GWP_{100} from the fifth assessment of the Intergovernmental Panel on Climate Change (IPCC, 2013).

2.2 RNG Production

Wet organic waste is converted into RNG through consecutive AD processes (Figure 2). The RNG production process takes organic matters, which mainly consist of proteins, lipids, starch, and carbohydrates, and converts them into monomers (acids, fatty acids, glucose, and sugars, respectively) through hydrolysis (Bhatt and Tao, 2020). With the monomers, acidogenesis generates volatile fatty acids and alcohols, which are then converted into acetate, CO_2, and H_2 via acetogenesis. Finally, CH_4 and CO_2 are generated through methanogenesis.

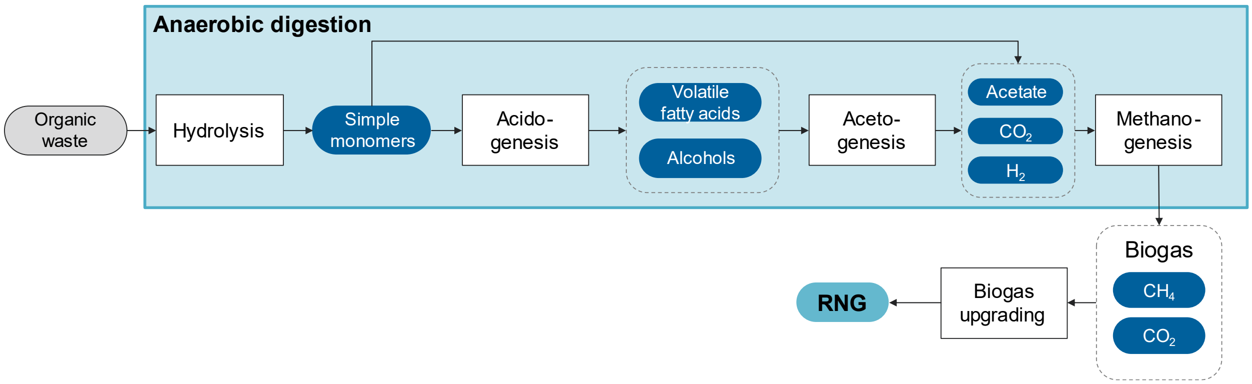


Figure 2. Process diagram of RNG production

Table 2a lists the mass/energy inputs/outputs of the conversion of wet waste feedstocks into biogas. All the inputs and outputs are expressed in terms of per dry kg waste treated (wet MT values are listed in Table A1 in the SI). Energy in the form of electricity and natural gas (NG) is required for converting waste into biogas, while other nutrients (corn steep liquor, diammonium phosphate, corn oil, sorbitol, and glucose) are required to support microbial activity in the AD reactor. Although these nutrients are not added in the commercial AD facilities, we consider them as additional inputs for enhancing AD operation to meet the target product yields. In addition to biogas, the process also produces digestate, which can either be used for land application or sent to landfill. The energy (heat and electricity) demands are mainly a function of feed flowrate, while there are also variations due to different compositions and moisture contents. Moreover, the amount of biogas produced from different types of waste varies, which may increase/decrease the heat and electricity demand. It is assumed that biogas is used to meet the internal heat demand for the AD process. Although not explicitly modeled in Bhatt and Tao (2020), we assume the AD facilities utilizing different types of wastes for biogas production would include an on-site combined heat and power (CHP) unit that would help to meet the heat and electricity demand of the plant with excess electricity exported to the grid. For example, the sludge to biogas process would require 1.2 MJ of heat for every kg of dry sludge processed, most (~90%) of which accounts for heat requirement in AD system, similar to reported values in literature (Coppinger et al., 1979; Han et al., 2016). FOG has the highest yield (26 MJ CH_4/dry kg waste feedstock). From the same 1 dry kg of feedstock, 13, 8.7, and 8.6 MJ of biogas is generated using food waste, sludge, and swine manure, respectively. The detailed parametric assumptions regarding the biogas production processes can be found in Bhatt and Tao (2020). Digestate is the residue of the AD process, and it has a high degree of biological stability (Rincón et al., 2019; Tambone et al., 2010), which means digestate may not be easily broken down to CO_2 or CH_4 through natural biodegradation, so most of the carbon in digestate would become sequestered carbon in landfills. We estimated emissions from digestate using 4.38 L CH_4/kg digestate, based on Tambone et al. (2010), with 50% CH_4 concentration. Note that there is 1 vol% CH_4 leakage during the AD process (Han et al., 2011).

Table 2. Mass and energy inputs and outputs of a) biogas production and b) LA production (per dry kg of waste feedstock) (Bhatt et al., 2020; Bhatt and Tao, 2020)

		a) Biogas Production				b) LA Production			
Inputs	**Unit**	**Sludge**	**Food Waste**	**Swine Manure**	**FOG**	**Sludge**	**Food Waste**	**Swine Manure**	**FOG**
NG [a]	MJ	1.2	0.16	0.65	0.45	1.3	0.17	0.72	0.49
Electricity [b]	kWh	0.039	0.10	0.26	0.32	0.39	0.67	0.49	0.98
Corn steep liquor	g	11	16	11	32	22	41	30	60
Diammonium phosphate	g	1.6	2.3	1.6	4.7	3.3	6.0	4.3	8.7
Corn oil	g	0.1	0.10	0.065	0.20	0.14	0.25	0.18	0.37
Sorbitol	g	0.7	1.1	0.73	2.2	1.5	2.8	2.1	4.1
Glucose	g	3.3	4.8	3.3	9.9	6.9	13	9.1	18
Process makeup water	L	0.017	0.08	0.21	0.26	0.70	1.3	0.44	2.0
Outputs	**Unit**	**Sludge**	**Food Waste**	**Swine Manure**	**FOG**	**Sludge**	**Food Waste**	**Swine Manure**	**FOG**
Biogas [c]	MJ	8.7	13	8.6	26				
Lactic acid	kg					0.36	0.66	0.48	0.97
CO_2	kg	0.35	0.47	0.42	0.57	0.15	0.13	0.093	0.46
Digestate	wet kg	1.9	1.6	1.8	1.0	0.51	0.42	0.53	0.32

[a] Biogas is used for internal heat demand for the biogas production case; fossil NG is assumed to be used for LA production.

[b] Detailed electricity demand is presented in Table A2

[c] CH_4 leakages are separately accounted for.

Biogas can be upgraded to RNG by removing CO_2 through many available biogas upgrading processes. Starr et al. (2012) summarized the energy and chemical requirements for various biogas upgrading processes in terms of 1 MT of CO_2 removal (Table A3 in the SI), which enables us to simulate different upgrading processes and compare the impacts. Table A2 also provides the rate of CH_4 loss during the process, which is a key factor in terms of life cycle GHG emissions results. The dominant biogas upgrading technologies in the market are pressure swing adsorption (PSA) and water scrubbing, while other technologies, including amine scrubbing, membrane separation, and cryogenic separation, have become popular in recent years (Shen et al., 2015). Thus, the PSA process, with 3.5% CH_4 leakage, was set as a default biogas upgrading technology, and the impacts of using different biogas upgrading technologies were analyzed. Among the technologies presented in Starr et al. (2012), two biogas upgrading processes are excluded from this study (bottom ash for biogas upgrading and membrane separation) because of their low CH_4 purity and high CH_4 loss, which are not suitable for RNG production. Note that Starr et al. (2012) considered no additional inputs for removing impurities such as H_2S since these would be removed via filters before upgrading biogas. Once pipeline quality RNG is produced, it is assumed to be injected into nearby pipelines and transported 80 km to end-users. Note that RNG transportation involves CH_4 loss of 3.04 mg/MJ (for 80 km) and energy consumption of 1.19 MJ/MT-km (Dunn et al., 2013).

2.3 LA Production

The LA fermentation process has been studied to evaluate the feasibility of sustainable high-value chemical production from organic waste (Urgun-Demirtas, 2019). In the AD process, the main product in the fermentation broth is targeted for LA production by inhibiting the methanogenesis that generates CH_4 as presented in Figure 3 (Bhatt et al., 2020). We considered separating LA from fermentation broth using an electrodeionization (EDI) separation technology. In this study, the four types of waste feedstocks used for RNG production are also considered for LA production via a LA fermentation process.

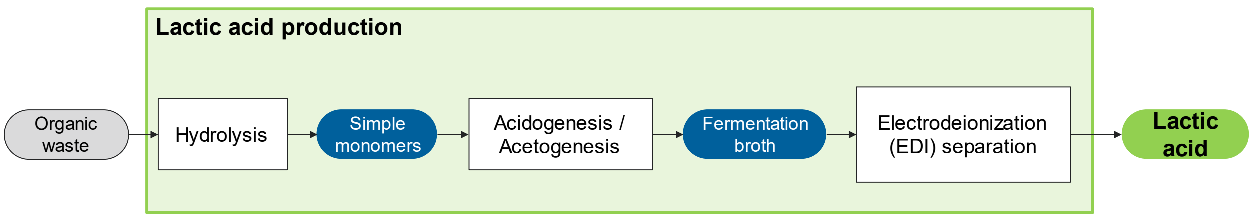


Figure 3. Process diagram of LA production

The detailed LA production model developed by Bhatt et al. (2020) uses the feedstock's composition of cellulose, lipid, protein, and lignin to determine the LA yield (L-LA). One specific difference between our study and the conditions in Bhatt et al. (2020) is the extraction process. Bhatt et al. (2020) modelled the extraction of LA through a pertractive membrane using tri-octyl-phosphine oxide (TOPO) as the solvent. This is a cost-effective separation process in which acids are continuously pulled across a membrane with the help of the solvent. In the current study, we chose a different separation process, EDI separation technology, instead of the membrane technology used in Bhatt et al. (2020). EDI separation technology is able to continuously extract more than 90% of LA: Ion exchange resins enhance the conductivity of the solution to selectively extract the acid from the fermentation broth at high purity. The resins are continuously regenerated by an electric field, providing cost benefits (Boontawan et al., 2011; Handojo et al., 2019). While EDI offers continuous separation with high-purity products (Handojo et al., 2019), note that it is an electricity-intensive process.

The mass and energy inputs and outputs of LA production are presented in Table 2b. LA requires around two to three times more chemical inputs than biogas production, while heat requirements are comparable between the two. However, due to the very high electricity requirements for the EDI process, total electricity inputs for LA production per dry kg waste are much higher than those of biogas production. As in RNG production, there is a significant variation in LA yield, which ranges from 0.36 to 0.97 kg/dry kg waste. Since the electricity inputs for the separation process depend on the amount of LA produced, electricity inputs also significantly vary by type of waste. Unlike RNG production, which uses heat from biogas combustion, LA production is assumed to use fossil NG to support internal heat demand.

2.4 Displaced Counterparts

When comparing the RNG and LA production pathways with other waste management practices (per weight of treated waste), the benefits of generated products also need to be accounted for. Once RNG is produced, it can be assumed that fossil NG can be displaced; it is estimated that the fossil NG production pathway in the U.S. has 12.4 gCO_2e/MJ fossil NG from NG recovery to use (excluding combustion emissions) (Wang et al., 2020), which can be accounted for as emission credits for RNG production. Similarly, the cradle-to-gate GHG emissions of conventional LA production from corn and corn stover, which are estimated at 1.2 and 0.3 $kgCO_2e$/kg LA, respectively, are accounted for as an emission credit for LA produced (Wang et al., 2020). Detailed LCA information on conventional fermentation LA production can be found in Adom and Dunn (2017) and Dunn et al. (2015).

2.5 Avoided Business as Usual (BAU) Scenarios

When LCA results of waste-derived products are expressed in terms of energy produced (e.g., gCO_2e/MJ RNG) or chemical produced (e.g., $kgCO_2e$/kg LA), it is important to take into account the emission credits stemming from the avoided BAU cases in calculating the CIs of the products. This is because there must be an existing waste treatment plant to handle waste feedstocks used for RNG/LA production, since waste is not intentionally generated and waste management is regulated (Lee et al., 2017, 2016b).The BAU scenarios for the four waste cases are presented in Figure 1.

For sludge, AD is the typical treatment method used in the U.S., and most sludge treatment facilities use biogas to meet internal heat demand (Shen et al., 2015). Thus, if sludge is used to generate RNG or LA instead, conventional sludge AD with biogas combustion is likely to be displaced. For the avoided sludge BAU case, we used the same AD parameters presented in Table 2, while removing emissions from biogas upgrading, CH_4 leakage during upgrading, and RNG transportation. Instead, we accounted for biogas combustion emissions. Since the energy content in biogas generated from AD is sufficient to cover the heat demand, no external fossil NG is needed.

In the United States, 56% of food waste goes into landfills in 2018 while the rest is managed for beneficial uses (e.g., animal feed and land application) (U.S. EPA, 2020). Because waste with specific uses may not be diverted for RNG production, we considered a process that assumes food waste without specific use is instead diverted from landfills. Similarly, we assumed FOG is diverted from landfills. Once organic waste is landfilled, it decomposes to CH_4 and CO_2 in an anaerobic condition, which is very similar to AD processes. The major difference is that biogas generated in AD facilities is captured and used, while landfills emit more non-captured CH_4 to the atmosphere. This is because landfills start generating landfill gas even before the landfill is capped and landfill gas collectors are installed. In order to estimate landfill gas emissions, landfill operating conditions and the landfilled waste are characterized (Lee et al., 2017). The fraction of degradable organic carbon that is dissimilated (DOC_F) defines how much of the carbon in waste is converted to landfill gas, which is mainly dependent on the types of feedstock. In this study, we estimated the DOC_F of food waste and FOG at 0.64 and 0.79, respectively, using the AD simulation parameters in Table 2 and emissions from digestate (Tambone et al., 2010). For landfill parameters such as landfill gas collection efficiency (59%), oxidation factor (36%), and CH_4 concentration (50 vol%), we used the values from Lee et al. (2017, 2016b). Note that collected landfill gas is assumed to be flared, since it is likely that waste for energy production would be diverted from landfills that do not have costly infrastructure (electricity generation).

To quantify emissions from current swine management practices, we used the parameters investigated by Han et al. (2011) and updated the properties of animal waste using the values in Table 1. In this study, we used U.S. average swine management by default. Each type of animal manure management, such as deep pit, pasture, solid storage, and anaerobic lagoon, was analyzed to show the changes in the GHG emissions results.

3 Results and Discussion

3.1 Life Cycle GHG Emissions

The LA pathway generally has a higher carbon conversion rate than the RNG pathway (Figure 4). It should be noted that this difference is in part due to biogas leakage and the use of biogas to meet internal heat demand. The total biogas production prior to these effects is shown in light blue at the tops of the RNG bars. The difference is more significant for the food waste and swine manure feedstocks than the sludge and FOG feedstocks. The differences between RNG and LA stem mainly from varying amounts of fermentable components (carbohydrates, proteins, and lipids). For example, the carbohydrate component of food waste and swine manure is larger than other components, and each mole of carbohydrate is assumed to produce 2 moles of LA. On the other hand, for RNG production, the CH_4 composition in biogas is low for food waste and swine manure (56% in food waste and 53% in swine manure) leading to low carbon conversion; a high fraction of the carbon is lost to unusable CO_2 (Bhatt and Tao, 2020). Note that the LA production pathways use additional fossil carbon from external NG, ranging from 0.5% to 4.8% of waste carbon inputs, which is not shown in Figure 4.

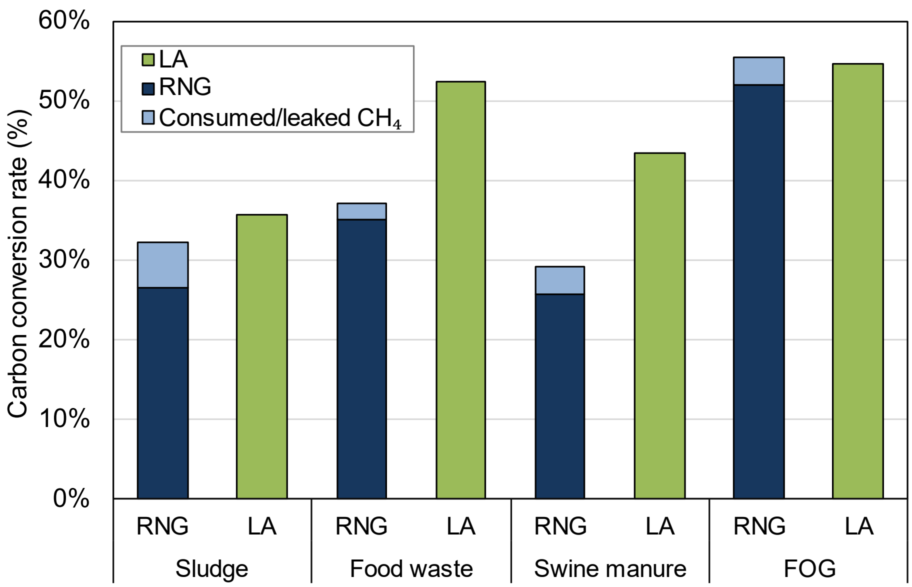


Figure 4. Carbon conversion rates (%) of RNG and LA production pathways

Figure 5 presents life cycle GHG emissions per dry kg of waste. The amount of carbon in one MT of waste is estimated at 16, 127, 31, and 71 kg for sludge, food waste, swine manure, and FOG, respectively. Thus, the results per wet weight of waste are highly influenced by moisture and carbon content. However, since wet weight of waste is a typical unit used in the waste management field, corresponding results in terms of wet MT of waste are presented in Figure A1 in supplementary information (SI). We explicitly present biogenic carbon uptake, which brings significant negative emissions for all cases because not all carbon is converted to products/emissions; there is a high fraction of carbon that remains in landfills.

Biogenic carbon uptake is the same regardless of the waste management technology; the significant differences arise from the carbon content of the waste feedstock. It is important to note that Figure 5 results can be used to compare the environmental impacts of different waste management practices, and RNG or LA production can be considered as a new waste management practice generating a product. Therefore, these waste valorization scenarios would have emission displacement credits for the products that other waste management practices may not have.

RNG and LA production pathways have significantly lower GHG emissions than BAU waste management practices. First, we can identify different trends in BAU and waste valorization cases. While the life cycle GHG emissions (black bars) of all RNG and LA cases show negative emissions, BAU cases have much higher positive emissions except for the sludge AD case. For sludge, the BAU case flares all generated biogas except for leaked CH_4, while all chemical inputs to the RNG production case (accounted for in the conversion step) are assumed to be the same, which leads to it having slightly higher emissions compared to the RNG case. Still, the sludge BAU case has negative life cycle GHG emissions, mainly due to the impact of biogenic carbon uptake.

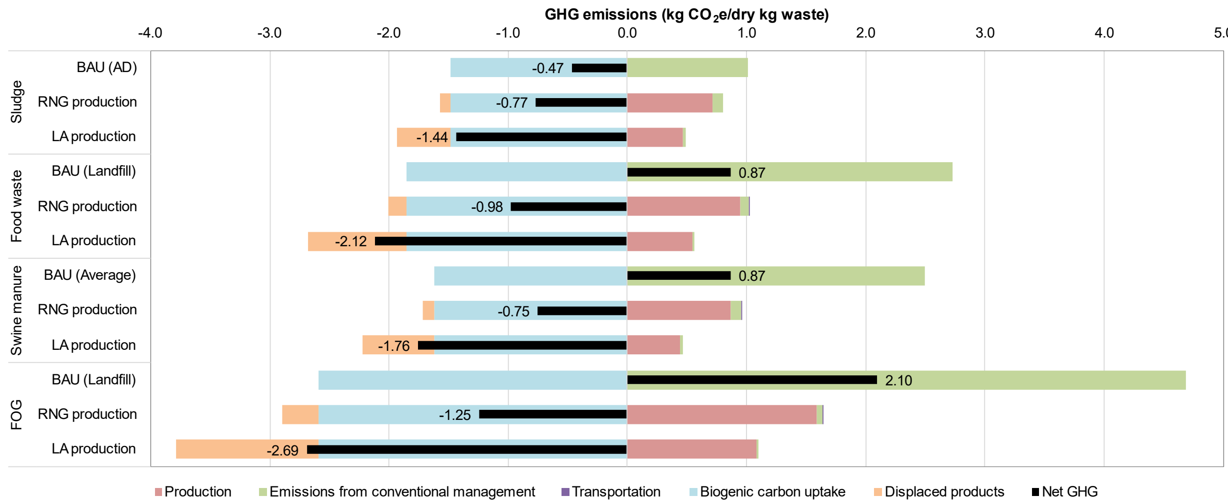


Figure 5. Life cycle GHG emissions of RNG and LA production pathways compared to BAU waste management practices in terms of dry kg waste

In the BAU cases of food waste and FOG, significant CH_4 emissions are caused by fugitive CH_4 emissions from landfills. With 59% landfill gas collection efficiency and a 36% flaring/oxidation factor (Lee et al., 2017), these fugitive CH_4 emissions make significant contributions to global warming impacts. For food waste, 36% of carbon remains in the landfill, and the rest becomes CH_4 and CO_2 emitted to the atmosphere. A portion of the CH_4 is converted to CO_2 via combustion or oxidation in the landfill cover. The fugitive CH_4 emissions portion alone causes 1.68 kgCO_2e/dry kg. Similarly, fugitive CH_4 from FOG results in 2.89 kgCO_2e/dry kg. Overall, the effect of landfill gas emissions overwhelms the biogenic carbon uptake, which generates positive life cycle GHG emissions from landfills: 0.87 and 2.10 kgCO_2e/dry kg waste for food waste and FOG, respectively. Swine manure management practices also involve a significant amount of fugitive CH_4 emissions: 1.41 kgCO_2e/dry kg waste, assuming the U.S. average swine manure management, which would vary depending on the animal waste management type.

For both RNG and LA production, emissions during the conversion processes are much lower than the positive GHG emissions from the corresponding BAU cases. For RNG production, emission impacts mostly come from CH_4 leakage and CO_2 from AD and biogas combustion. On the other hand, for LA production, NG and electricity consumption play an important role (54%–77% of total conversion emissions) along with process CO_2 emissions. There are minor emissions from digestate from both RNG and LA production pathways, shown in green in Figure 5. Overall, even with much higher electricity requirements, LA pathways have lower emissions during the conversion processes than those of RNG.

Unlike the BAU cases, waste valorization pathways generate products: RNG and LA. Thus, there are emission credits (orange in Figure 5) from displacing conventional counterparts (i.e., fossil NG and corn LA), which further reduce the life cycle GHG emissions of these pathways. For example, FOG-derived LA brings -1.20 kgCO_2e/dry kg of emission credits, while FOG-derived RNG brings -0.3 kgCO_2e/dry kg. For all cases, LA production cases have higher emission credits than those of RNG production, mainly because 1) LA's conversion efficiency is higher than RNG's (Figure 4), and 2) displacement of conventional LA brings more benefits, even with the same carbon conversion efficiency. Since conventional corn fermentation for LA production requires significant heat (NG) inputs, the displacement impact of corn-derived LA brings high GHG emission reduction benefits.

Ironically, high RNG yield leads to high CH_4 leakage, which negatively influences the life cycle GHG emission results. FOG has relatively higher AD process emissions, mainly because of its high CH_4 leakage led by high RNG yield. CH_4 leakages (3.5% for biogas upgrading with PSA and 1.0% for AD) overwhelm the impact of all other AD-related emissions. Similarly, the electricity requirement for the EDI LA production process is closely related to LA yield: Higher LA production tends to lead to higher GHG emissions embedded in electricity inputs. Figure A2 in the SI presents the sensitivity analysis results of the major pathways of swine manure pathways for three scenarios (BAU, RNG production, and LA production). The results show that conventional waste management practices present much wider variation in GHG emissions compared to RNG and LA production pathways although the trend stays the same.

The CIs of RNG or LA derived from waste feedstocks can be compared with those of their counterparts (i.e., conventional natural gas or LA). In this case, using waste for RNG or LA production inherently diverts waste from BAU because, unlike other feedstocks, waste is not intentionally generated to produce RNG or LA. Thus, emissions from BAU can be avoided.

In Figure 6a, we present the results in functional units of MJ RNG. The figure shows that the trend of life cycle emissions (black bars in Figure 6a) is quite different from that of Figure 5. Figure 6a now has positive GHG emissions for RNG from sludge (27 gCO_2e/MJ), and RNG from swine manure has the lowest CI (-146 gCO_2e/MJ). Other RNG production pathways from food waste and FOG generate -87 and -68 gCO_2e/MJ, respectively. Note that all RNG pathways have much lower CIs compared to that of fossil NG (70 gCO_2e/MJ), which means RNG from these waste feedstocks provides significant GHG emission reduction benefits.

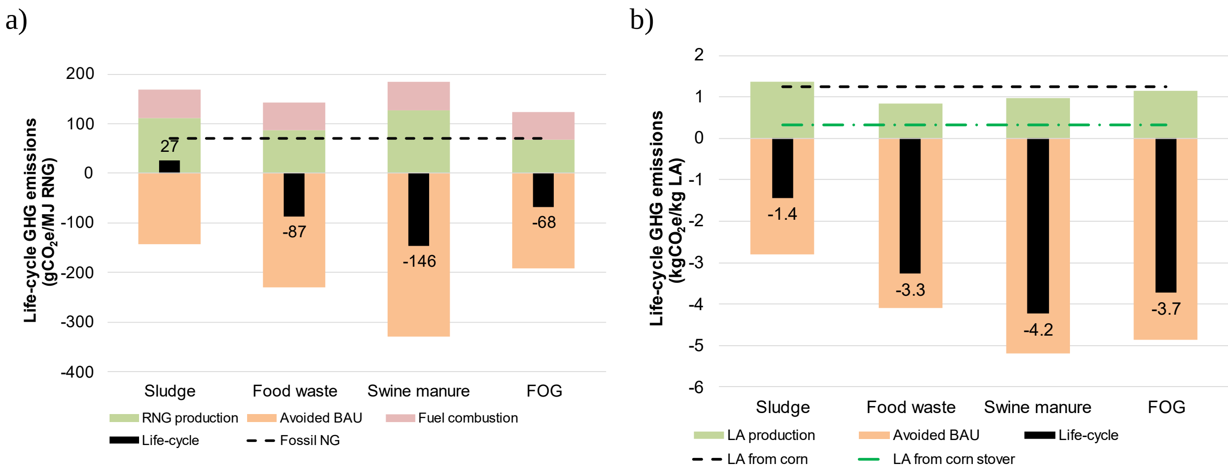


Figure 6. Life cycle GHG emissions of (a) RNG (gCO_2e/MJ RNG) and (b) LA ($kgCO_2e$/kg LA) along with those of their counterparts (fossil NG and conventional LA, respectively)

Avoiding BAU cases brings emission credits. Note that the biogenic carbon uptake credits presented in Figure 5 are offset between BAU and alternative cases. Thus, we do not present the impact in Figure 6. RNG pathways have high emission credits (negative emissions) mainly due to avoided fugitive CH_4 emissions from landfills and animal waste treatment facilities (Figure 5). The sludge pathway has lower emission credits because of the slightly higher GHG emissions from AD flaring compared to RNG production. The avoided emission credits are estimated at -142, -230, -329, and -192 gCO_2e/MJ for sludge, food waste, swine manure, and FOG, respectively. Therefore, more environmental benefits can be attained by diverting waste that currently generates significant GHG emissions. For example, diverting waste from poorly managed swine manure management facilities would provide more GHG emission reduction benefits compared to taking from improved facilities. The avoided BAU emissions in Figure 6 are also influenced by RNG yield. Although the BAU case of FOG has higher CH_4 emissions than that of swine manure in Figure 5, FOG has fewer emission credits because less FOG than swine manure is needed to generate 1 MJ of RNG.

There are two main reasons for the low CI of RNG from swine manure. First, its low RNG yield requires more feedstock input for the same MJ RNG production compared to other feedstocks. Second, it has high avoided BAU emission credits due to, again, its low yield and BAU's high GHG emissions. Although higher RNG yields generated higher fugitive emissions in Figure 5, the impact does not show up in MJ results (Figure 6a) because CH_4 leakage is proportional to RNG production. Instead, the swine manure case has higher RNG production emissions due to its higher heat demand per MJ than others.

Stakeholders seek to generate fuels with low CIs to potentially receive incentives through carbon reduction programs like California's low carbon fuel standard (LCFS). The life cycle GHG results in terms of MJ of fuels, like those shown in Figure 6a, are generally used to gauge the success of the development of new fuel production pathways. It appears that using swine manure for RNG production provides the best results in terms of GHG emission reductions because it has the lowest CI. However, when we express the GHG emission results on a MJ basis, we see that the pathways with high conversion efficiency (high yield) lower not only the emissions but also the emission credits. We will discuss the impact of the CI and the yield in the following section.

Like RNG production pathways, waste-derived LA production presents potential GHG emission benefits in terms of kg LA production (Figure 6b). Compared to the conventional LA production pathways, with life cycle GHG emissions of 1.2 and 0.3 $kgCO_2e$/kg LA from corn and corn stover, respectively, all waste-derived LA production pathways have negative life cycle GHG emissions, ranging from -1.4 to -4.2 $kgCO_2e$/kg LA. These major reductions also come from avoiding BAU emissions. In addition, Table 2 shows that heat requirements for LA production through LA fermentation are much lower than typical fermentation processes, which reduces the life cycle GHG emissions of LA produced via LA fermentation.

3.2 Economic Potential of the Products

CIs (gCO_2e/MJ RNG or $kgCO_2e$/kg LA) have been the metric with which to compare various pathways' carbon footprints in a consistent manner. In the energy and transportation sector in particular, having a low CI is interpreted as being more sustainable compared to other pathways. Many RNG pathways have been certified as fuels with negative CIs under California's LCFS by considering their high avoided BAU emissions (CARB, 2020a). These are even lower than those of biomass-derived fuels, which are already lower than those of fossil fuels, which is why there has been increasing interest in RNG production in California. In this case, swine manure is considered an ideal feedstock because of its low CI (-146 gCO_2e/MJ). It is clear that swine manure brings more GHG emission savings, in terms of MJ of RNG, when it is compared to a fossil fuel baseline (gasoline baseline in 2020 under LCFS: 92 gCO_2e/MJ [CARB, 2020b]).

However, RNG yield needs to be considered along with the CI reduction. As presented in Table 3, RNG production from one wet MT of waste varies from 286 to 2,960 MJ/wet MT (sludge and food waste, respectively), which means we would have around 10 times more RNG production from food waste than from the same amount of sludge. Therefore, carbon emission reductions per MT of waste used are determined by both the CI and RNG yield. While swine manure presented the lowest CI, food waste-derived RNG brings the highest carbon emission savings per MT of waste treated (530 $kgCO_2e$/wet MT waste). When we consider carbon credit of US$200/MT of CO_2 emission reduction, current carbon credit price under LCFS (CARB, 2020c), we gain $106/wet MT food waste from emission reduction credit on top of the revenue from selling RNG. On the other hand, swine manure generates $25/wet MT waste due to its low RNG yield.

Table 3. CIs, emission reductions, and potential carbon credits of generating RNG from sludge, food waste, swine manure, and FOG

	Sludge	**Food Waste**	**Swine Manure**	**FOG**
CI (gCO_2e/MJ)	27	-87	**-146**	-68
Carbon emissions reduction from the baseline gasoline CI [a] (gCO_2e/MJ)	65	179	**238**	160
RNG production (MJ/wet MT waste)	286	**2,960**	530	**2,450**
Carbon emission reduction through RNG production ($kgCO_2e$/wet MT waste)	19	**530**	126	**391**
Potential carbon credit [b]	3.7	**106**	25	**78**

($/wet MT waste)				

[a] Baseline gasoline: 92 gCO_2e/MJ

[b] $200/MT CO_2 emission reduction

Figure 7 compares the monetary values of RNG and LA produced from four types of wet waste. The RNG price ranges $7–$45/mmBtu RNG (0.66–4.3¢/MJ) in the U.S. (American Gas Foundation, 2019), while the LA price ranges $1,400–$2,400/MT LA (Bhatt and Tao, 2020; Farzad et al., 2017; Taylor et al., 2015). We selected $18/mmBtu RNG (1.7¢/MJ) and $1,450/MT LA for the baseline RNG and LA prices. For RNG, we also accounted for carbon emission reduction credits using $200/MT CO_2 ($100–$220/MT CO_2 reduction) representing current LCFS credit transfer activities (CARB, 2020c). Note that we only accounted for carbon credit for RNG production, since there are no programs incentivizing reductions in emissions in chemical production at this moment. Error bars present high and low cases with the ranges provided.

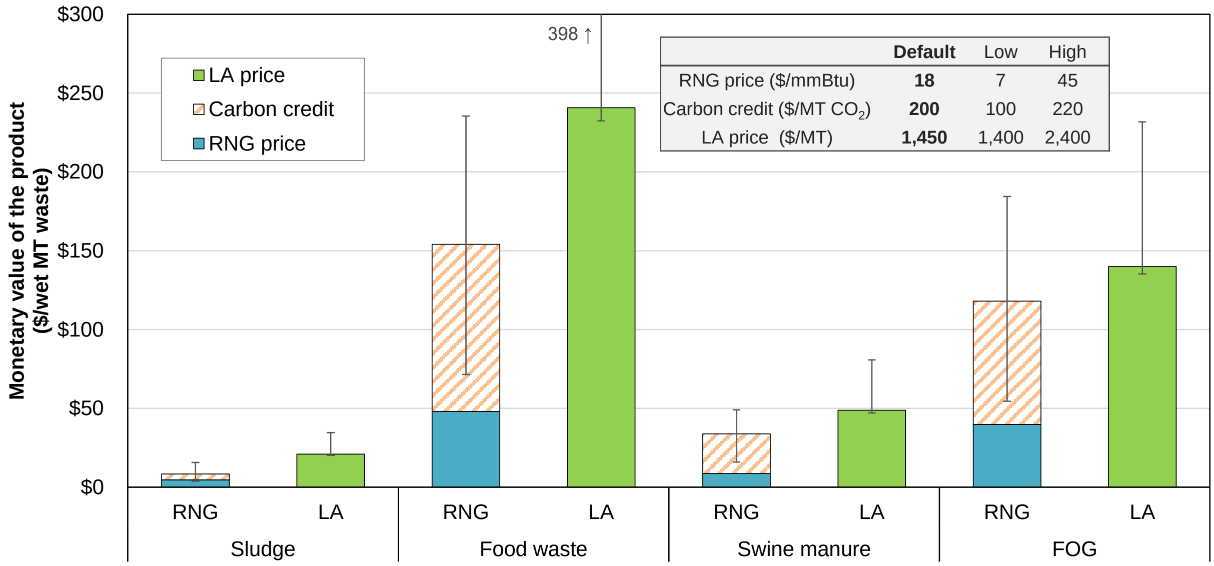


Figure 7. Monetary values, including the prices of the products and carbon credits, of RNG and LA produced from sludge, food waste, swine manure, and FOG

Figure 7 shows that LA can generate much higher revenue from product sales because its price and yield are higher than RNG's. Even without considering $200/MT CO_2 emission credits, LA can generate more revenue from the same amount of wet waste feedstocks. Food waste generates the highest revenue from one wet MT due to its high yield (per wet MT), followed by FOG, swine manure, and sludge. The orange hatched bars of the RNG pathways indicate the additional monetary values achieved through carbon emission reduction under an emission reduction scheme (e.g., LCFS). It shows that carbon credits can be a strong driver for RNG production even though RNG's price may be insufficient to compete with LA production without the credit. As shown in Table 3, the significant CI reduction of swine manure does not bring much benefit in terms of wet MT waste treated.

Table 4 presents techno-economic analysis (TEA) results of RNG and LA production with the same datasets/assumptions (mainly from Bhatt and Tao [2020] for RNG and Bhatt et al. [2020] for LA). It shows that LA has slightly lower capital costs, while operating costs are higher than RNG's mainly due to its high electricity requirements for acid extraction. Thus, while LA can generate higher revenues from the products (Figure 7), operating costs should be also considered. Note that no other costs for BAU cases are considered (e.g., avoided tipping fees for landfills), which may work as additional economic benefits. Also, for the RNG case, biogas upgrading is not included in the TEA (Bhatt and Tao, 2020). Note that the TEA results for LA have been updated from Bhatt et al. (2020), as we have assumed the use of EDI for the acid separation process instead of pertractive membrane separation with TOPO solvent.

Table 4. Installed capital costs and operating costs of the simulated RNG and LA production facilities

Feedstocks	**Sludge**		**Food Waste**		**Swine Manure**		**FOG**	
Scale	**6,800 MT/day**		**230 MT/day**		**200 MT/day**		**180 MT/day**	
Products	**RNG**	**LA**	**RNG**	**LA**	**RNG**	**LA**	**RNG**	**LA**
Installed capital costs (million$)	55.4	40.1	24.6	20.3	9.9	6.9	12.9	8.6
Operating costs (million$/year)	7.1	12.0	2.2	4.3	1.1	1.7	1.5	2.0

RNG: (Bhatt and Tao, 2020)

LA: (Bhatt et al., 2020) for acid separation, EDI is used

No feedstock cost is included. No avoided cost for BAU cases (e.g., tipping fees) and carbon credits are considered.

3.3 Potential RNG/LA Production and Associated GHG Emission Reductions in the U.S.

Skaggs et al. (2017) evaluated the available waste resources in the U.S., which are estimated at 13, 14, 38, and 5.4 dry MT/year for sludge, food waste, animal waste, and FOG, respectively. If all available waste resources in the U.S. were used to generate RNG, potential RNG production is estimated to be 90, 163, 285, and 131 billion MJ for sludge, food waste, animal waste, and FOG, respectively, using the RNG yields in this study (for animal waste, swine manure values are used). Considering that total U.S. NG consumption in 2019 was 34 trillion MJ (32 quadrillion BTU) of which NG for transportation was 3.0%, RNG from waste can support around two-thirds of the current U.S. NG use for transportation if all waste resources are used for RNG production.

With the same waste resource potential, we can generate a total of 37 MMT of LA per year (4.5, 9.1, 18.1, and 5.2 MMT of LA from sludge, food waste, animal waste, and FOG, respectively). Considering that the total global LA market is around 0.47 MMT in 2014, which is expected to grow to 1.84 MMT in 2022 (Credence Research, 2016), even a small share of available U.S. waste resources can be used to meet the global LA demand. This means GHG emission reduction potential by LA production is limited by the LA market size rather than the amount of waste feedstocks.

Figure 8 presents the potential GHG emission reduction through RNG and LA production. For the baselines, we selected the CIs of gasoline (92 gCO_2e/MJ) and corn-derived LA (1.2 $kgCO_2e/kg$). If we assume that all waste resources in the U.S. are converted into RNG or LA, estimated total emission reductions are 128 and 178 MMT CO_2e/year for RNG and LA, respectively. However, if we cap the total LA production at the expected global LA demand in 2022, only 5% of U.S. wet waste resources are needed to saturate the global LA market. The red bars represent the potential emission reduction (8.9 MMT CO_2e/year) from potential LA produced from 5% of each waste feedstocks. Thus, while LA can bring higher GHG emission reduction from the same amount of waste compared to RNG, the market can be saturated much more quickly than the NG market. Note that potential expansion of the PLA market can boost the LA market in the future.

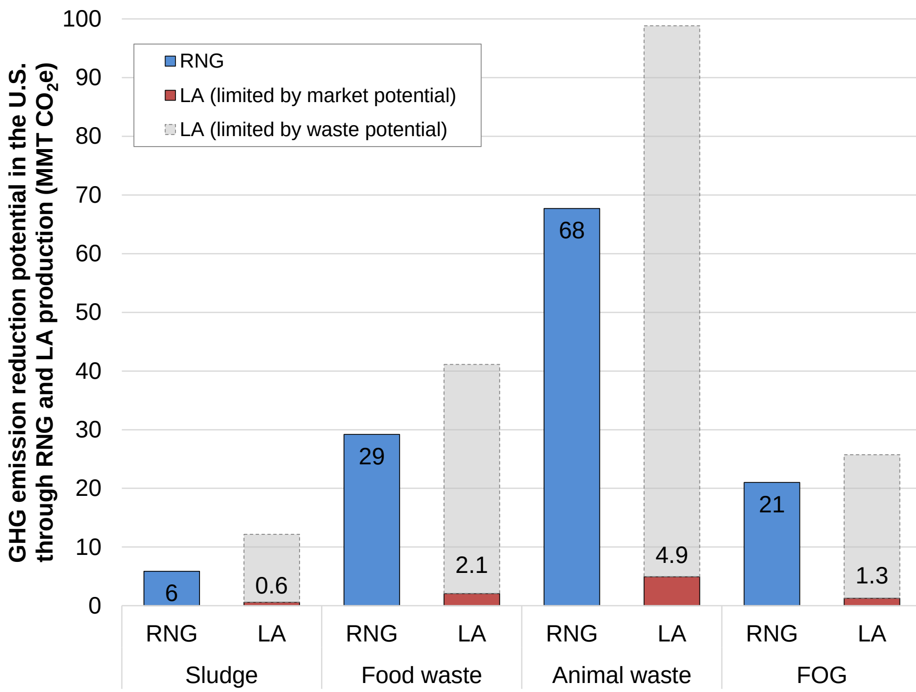


Figure 8. GHG emission reduction potential in the U.S. through RNG and LA production using waste feedstocks.

3.4 Discussion

Variations in GHG emissions of BAU cases influence overall GHG emissions. For example, if food waste is diverted from landfills with active landfill gas collection (life-time collection efficiency of 79%) instead of moderate landfill gas collection, avoided emission credits shrink, leading to a CI of -54 gCO_2e/MJ RNG and -2.2 $kgCO_2e/kg$ LA. For swine manure, depending on the avoided BAU technologies, results vary substantially, from -189 gCO_2e/MJ RNG and -4.9 $kgCO_2e/kg$ LA (anaerobic lagoon) to 42 gCO_2e/MJ RNG and -1.3 $kgCO_2e/kg$ LA (pasture). For AD, biogas upgrading technologies and associated CH_4 leakage rates influence the GHG results the most. For example, the CI of RNG from food waste varies from -108 gCO_2e/MJ RNG (amine scrubbing) to -84 gCO_2e/MJ (organic physical scrubbing) mainly due to different CH_4 leakage rates. In this study, we set the default conditions of most likely BAU scenarios for the selected feedstocks and used the best available data that represent the conditions. However, actual BAU conditions and corresponding parameters should be used to evaluate the actual impact of diverting waste for fuels/chemicals production, because the BAU conditions and parameters significantly influence the LCA results.

There are many ongoing research projects focused on increasing RNG yield by converting CO_2 from AD into CH_4 through various CO_2 utilization technologies, while we considered only typical AD processes with biogas upgrading in this study. CO_2 utilization technologies typically require additional hydrogen and/or electricity inputs. Depending on the CIs of the input hydrogen/electricity, the CI of the RNG can be further reduced or even increased.

For LA production processes, Bhatt et al. (2020) found that LA produced via the LA fermentation process from waste feedstocks could have lower market selling prices compared to its counterparts from larger scale facilities. Thus, LA production through LA fermentation has significant potential from both environmental and economical perspectives. In this study, we relied on the process modeling performed by Bhatt et al. (2020) with the modification in the separation/extraction process. Although we simulated the LA produced from various waste feedstocks via LA fermentation using the most up-to-date information available, there are still technical challenges such as acid toxicity and high cost of recovery/separation that need to be addressed. In addition, this study is based on a target scenario converting wet wastes into 100% LA, which requires additional refinements to reflect actual operation aspects as the research progresses.

In this study, monetary emission reduction credits for LA are not accounted for, although the additional monetary benefit through carbon reduction credits for LA can be expected to be higher than those of RNG. To consider such subsidies in chemical production, it is important to define the baseline chemical production pathways, like the fossil fuel production baselines, that have a consensus on CIs that is supported by various studies. Although the current analysis uses the LA production pathways analyzed in previous studies (Adom and Dunn, 2017; Dunn et al., 2015), further harmonization is needed to define a broadly used baseline CI for the chemicals displaced.

4 Conclusions

There is a significant amount of waste in the U.S. that is generated and needs to be treated every day but that also has a considerable potential for waste valorization. This study discusses the GHG emission reduction impacts of the combinations of waste feedstocks and final products (RNG and LA) via different conversion routes. The results show that using waste feedstocks can lead to having significant GHG emission reduction benefits, regardless of the types of feedstock or the types of products, compared to conventional waste management practices or the counterparts of the waste-derived products. However, the results also clearly show that GHG emissions results vary depending on the waste resources used, conversion or separation technologies, and the credits that apply due to displaced products. Each waste resource would bring embedded avoided emissions, and BAU plays a significant role in determining the life cycle GHG emissions of the waste treatment practices or fuel/chemical production pathways. This work also shows that CI alone cannot be used to demonstrate the sustainability of a product generated from waste resources, because the GHG emission reduction can be magnified in terms of MJ or kg of the product when linked with low feedstock conversion efficiency by having higher avoided emissions. Thus, the CI needs to be considered along with the fuel/chemical production potential for informed decision making.

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the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.

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The images of waste, trash can, flame, beaker, and sewer in the graphical abstract are public domain, courtesy of the Noun Project.

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