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Biomethane production potential of slaughterhouse waste in the United States

Shunli Wang[a,*], Umakanta Jena[b], Keshav C. Das[a]

[a] College of Engineering, University of Georgia, Athens 30605, USA
[b] Chemical and Materials Engineering, New Mexico State University, Las Cruces 88003, USA

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ABSTRACT

Anaerobic Digestion (AD) is a promising technology to treat slaughterhouse waste (SHW) for the bioenergy production, nutrient recovery, and pathogen reduction. Three scenarios of estimating the biomethane potential from SHW of the US and the individual States have been conducted in this study. The US meat producers discharged 18.4 million metric ton (MT) SHW in 2016, which can potentially generate 22.7×10^9 kWh of biomethane. In Texas State, up to 2.3×10^9 kWh year^{-1} of energy can be potentially produced from AD of SHW and up to 106.3% of natural gas currently used in the Nebraska State for electricity generation can potentially be replaced with biomethane produced from the AD of its SHW. The technical challenges using SHW as the feedstock of AD process in the US have been summarized, including nitrogen and sulfur inhibition, foaming, sterilization, digestate disposal, supply chain etc. In addition, case studies were conducted by proposing an AD plant treating SHW from a typical slaughterhouse in a U.S. State that mostly processes the broiler, swine, and bovine. In our case studies, a net energy of 17,009–85,278 kWh d^{-1} is estimated to be generated from such AD plant. Therefore, producing biomethane from SHW can significantly promote bioenergy production in the US, thus enhancing the quick reach of bioenergy development targets set at the Federal and State levels, while overcoming the technical and management barriers of using SHW.

1. Introduction

The meat industry of the United States (US) produced 41.5 million metric tons (MT) of ready-to-eat meat, including chicken, pork and beef, and discharged approximately an equal amount of slaughterhouse waste (SHW) in 2016 [1–3]. These wastes which mainly include manure, blood, feather, and viscera contain a high proportion of protein and lipid, and are typically processed in a rendering plant where they are converted to byproduct meal as nutrients supplement in animal food in the US [1]. The rendering process requires energy-intensive operations such as centrifuging, cooking or drying. The energy consumed in rendering of one MT SHW was reported to be 70 kWh electricity and 639 kWh process fuel [4], most of which is generated from non-renewable fossil fuels [5]. In addition, due to the risk of transmissible spongiform encephalopathy, the economic value of rendering products is being reduced, and in many cases, SHW should be disposed as wastes [6,7]. Hence, for acquiring economy, environment and energy sustainability of the meat industry, exploring alternative ways to treat SHW has become a great necessity.

Anaerobic digestion (AD) has been used as a promising technology to treat SHW, due to benefits of biomethane production (a bioenergy source) and low environmental footprints (greenhouse gases reduction, nutrient recovery, etc.) [6,8]. SHW are composed of high levels of organic matter, mainly proteins and lipids [9,10] and have been reported to have high biomethane production potential in numerous studies (e.g. Hejnfelt and Angelidaki [9]; Salminen and Rintala [11]; Ware and Power [10]). In the biochemical pathways converting the SHW into intermediates and biogas in the AD, the SHW are first hydrolyzed into amino acids and long-chain fatty acids (LCFA) in the hydrolysis process, and then converted to ammonia, hydrogen sulfide, volatile fatty acids (VFA), hydrogen, and carbon dioxide in the process of acidogenesis and acetogenesis. Finally, biogas composed of methane and carbon dioxide is generated by methanogens in the methanogenesis process [11]. The biochemical methane potential (BMP) of blood and offal were measured as approximately 0.5 and 0.7 $m^3\,kg^{-1}$ VS, respectively [11]. Due to the high BMP of SHW, many researchers have quantified the energy production potential from AD of SHW in different countries. For instance, Arshad et al. [12] estimated 102×10^6 kWh electricity year^{-1} is produced from AD of poultry wastes in Pakistan, and Abdeshahian et al. [13] found $\sim 8 \times 10^9$ kWh electricity year^{-1} can be potentially yielded

* Corresponding author.
E-mail address: wshl2000@uga.edu (S. Wang).

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Nomenclature

AD	Anaerobic digestion
BMP	Biochemical methane potential
CHP	Combined heat and power
DAF	Dissolved air flotation
EC	European Regulation
FiT	Feed-in-tariff
GA	Georgia
HRT	Hydraulic retention time
Iowa	IA
LCFA	Long chain fatty acids
MT	Metric tons
NE	Nebraska
OFMSW	Organic fraction of municipal solid waste
OLR	Organic loading rate
REC	Renewable energy credit
RPS	Renewable portfolio standard
SHW	Slaughterhouse waste
TCF	Trillion cubic feet
TeMP	Technical biomethane potential
ThMP	Theoretical biomethane potential
TS	Total solids
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
VFA	Volatile fatty acids
VS	Volatile solids

from AD of animal wastes in Malaysia. Therefore, AD of SHW produced from the growing meat industry could potentially offer the sound bioenergy production benefits and enhance the global environmental protection as well.

AD of SHW for bioenergy production was less studied compared to other AD feedstocks in the US, like animal manure and sewage sludge. In recent decades, US government agency (e.g. US Environmental Protection Agency (EPA)) and private businesses have planned for and managed a low carbon footprint environment, by producing more low-GHG fuel, like biomethane [14]. The state-level Renewable portfolio standard (RPS) implemented by twenty-nine states have planned to produce up to 40% electricity from renewable sources by 2030 [15]. To evaluate possibility of reaching this target, The National Petroleum Council estimated the US biomethane production potential which is 0.34, 0.06 and 0.9 trillion cubic feet (TCF) from landfill, wastewater sludge and agricultural manure, respectively, totaling 1.3 TCF per year (equivalent to energy of 376.3 billion kWh per year). This number equals to 13% of 2016 natural gas demand in the electricity generator sector (9.98 TCF) [16,17]. Shen et al. [18] reported that 484 GWh of annual biogas production can be gained from the co-digestion of waste activated sludge and other organic wastes in a large wastewater treatment facility of the US. Due to high biomethane production potential of SHW, use of it as the feedstock could significantly increase biomethane production of the US, thereafter helping quick reach of renewable energy exploration target. However, a comprehensive analysis of biomethane production potential of SHW in the US is still lacked and needed to investigate.

Although SHW have the high biomethane potential, technical challenges using such feedstock still exist and should be overcome in practical operations in the US. The challenges have been reported as ammonia toxicity [19], sulfur toxicity [20], foam creation [21], logistics of feedstock supply, etc. Such challenges should be summarized and overcome using the strategies which have been developed or developing in the AD process treating other common substrates.

The goal of this study is to estimate biomethane potential from AD of SHW in the US using three estimate scenarios. In the first scenario, the theoretical biomethane potential (ThMP) of SHW was calculated using the compositions of SHW and ThMP of carbohydrate, protein and lipid. In the second scenario, the BMP of SHW was calculated using the compositions of SHW, which was summarized from results of published literatures. In the third scenario, technical biomethane potential (TeMP) was calculated by considering the annual average temperature of each U.S. State. In addition, technical challenges and solutions of anaerobically treating SHW were assessed and discussed. Finally, for in-depth understanding on practical effects of the AD process, a full-scale biogas plant treating SHW from a typical slaughterhouse processing broiler, swine, or bovine in the US was proposed and the energy balance of the process was performed.

2. Data collection and calculation

2.1. Overall description

For estimating the biomethane potential, the data were collected from U.S. Department of Agriculture (USDA) reports [2,3] and literature studying the AD of SHW. The data from USDA reports included the animal numbers slaughtered in the US in 2016 and the average weight of animals. The compositions, quantity and BMP of SHW were collected from previous publications (Tables 1–3) to calculate the BMP of SHW from a unit of animal. The local temperature and natural gas consumption for electricity generation of each U.S. State were also included in the calculation and evaluation of BMP. Details of calculation are shown in following sections.

2.2. Animal population and SHW production

As the second-largest meat producer in the world, the U.S. processed 8.8 billions of broiler, 118.2 millions of swine, and 30.6 millions of bovine in 2016 [2,3]. Wastes from broiler, swine and bovine slaughterhouses used for calculating BMP were manure, blood, feather/bristle, viscera, meat tissue, and dissolved air flotation (DAF) sludge, according to their amount and the availability of published data. The live weight of an animal is varied depending on the species, age, feeding methods etc. and the ratio of SHW to live weight of an animal was calculated based on the information from previous publications and was applied in the calculation of SHW in the US.

2.3. Calculation of ThMP and BMP

ThMP in each U.S. State was calculated using SHW compositions, SHW weights (volatile solids (VS) base), ThMP of carbohydrate, protein, and lipid reported by Angelidaki and Sanders [22], and the animal numbers of each U.S. State (Eqs. (1)–(3)). For the convenient comparison to other energy sources, the BMP was expressed in kWh instead of volume. The heating value of methane used in the calculation was 11.3 kWh Nm^{-3}. Nm^3 is cubic meter at standard temperature and pressure condition (273 K and 1 atm).

$$\mathbf{Th_m = P\% \times Th_P + L\% \times Th_L + C\% \times Th_C} \quad (1)$$

where Th_m is ThMP of manure, blood, feather/bristle, viscera, meat tissue, or DAF sludge (kWh kg^{-1} VS); P%, L%, and C% are protein, lipid/fat, and carbohydrate content on VS base, respectively; Th_P, Th_L and Th_C are ThMP of protein, lipid/fat and carbohydrate, in the values of 5.61, 11.46 and 4.69 kWh kg^{-1} VS, respectively.

$$\mathbf{Th_m\_L = Th_m\_1 \times M\_1 + Th_m\_2 \times M\_2 + Th_m\_3 \times M\_3 + Th_m\_4 \times M\_4 + Th_m\_5 \times M\_5 + Th_m\_6 \times M\_6} \quad (2)$$