Renewable and Sustainable Energy Reviews 72 (2017) 254–268

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Approaches for adding value to anaerobically digested dairy fiber

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ARTICLE INFO

Keywords:
Dairy manure
Anaerobic digestion
Dairy fiber
Value-adding operations
Thermochemical processing
Bio-refinery

ABSTRACT

One of the consequences of the increase of large dairy concentrated feeding operations (CAFOs) is the abundance of dairy manure that needs to be disposed of or used in some way. CAFOs can become bio-refineries, harnessing the manure for heat, power, fuel, chemicals, fertilizers, fiber, wood composites, and biochar for production of multiple value-added co-products. The objective of this paper is to review options for using dairy manure fiber and its corresponding anaerobically digested (AD) fiber. Bedding for cows remains a common choice for employing the separated AD fiber. However, research has shown that AD fiber has potential for using it as a component of growth substrates used in container plant production systems, for producing composite materials, or as a feedstock for both chemical and thermochemical operations. Potential uses of AD fiber such as composite materials and liquid fuels are proposed based on experiences employing the manure and its fiber (both without a previous AD step and after AD). Thermochemical processing (e.g., liquefaction and pyrolysis) of AD fiber for fuels and chemicals has been conducted at laboratory level and still needs further study at larger scale. Gasification of AD fiber is a promising option since there is potential for integration of current methane production with methane produced from thermal gasification.

1. Introduction

Dairy farmers in several places worldwide are facing the difficulty of managing large amounts of dairy manure on concentrated animal feeding operations (CAFOs). In the United States (US), the midpoint size of dairies has risen from 275 to 900 cows, resulting in roughly 1800 large CAFO dairies with a wet-cow equivalent (WCE) herd size of 1000 or greater (many on the order of 5000, 10,000 or even 20,000). These large CAFOs produce over 50% of the milk supply [1]. With a production rate of 64–69 kg wet manure per cow per day (14–18% dry weight), these CAFOs, can produce a remarkable amount of manure and manure wastewater.

At such large scales, these dairy CAFOs are capable of becoming bio-refineries, harnessing the manure for heat, power, fuel, chemicals, fertilizers, fiber, wood composites, and chars/carbons, while mitigating climate, air, water and human health concerns associated with the manure [2,3]. A baseline for many CAFO bio-refinery visions is an anaerobic digestion (AD) operation for production of biogas and its resulting revenues from either combined heat and power (CHP) or renewable, compressed natural gas fuel (CNG), while also yielding significant environmental benefits related to methane capture and conversion, pathogen and odor destruction, and organic matter stabilization [4,5]. Unfortunately, adoption of even a baseline AD model on CAFOs within the US is currently limited to around 244 farms [6]. While several hurdles exist, a key limit to adoption rests on business economics with revenue from the most traditional biogas off-take, electrical power, simply not enough to supply a preferred return on investment [7,8]. However, incorporation of additional co-products and their revenues can have profound impacts towards financial viability. These additional revenue items can include tipping fees (as well as additional biogas/power) from off-farm organics, carbon credits, and of importance to this review paper, sales from the digested fibrous solid and/or its value-added products.

A key component within dairy manure is recalcitrant fibrous solids (fiber) surviving the cow's digestion process, which comprises roughly 40–50% of total solids (TS) in the as-produced manure [9,10]. This

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http://dx.doi.org/10.1016/j.rser.2017.01.054
Received 11 February 2016; Received in revised form 18 December 2016; Accepted 9 January 2017
1364-0321/

Table 1
Some characteristics of AD dairy fiber (dry basis).

Parameter	Unit	Value	
		Ref [10]	Ref [12]
TS (total solids)	%	24.43	–
VS (volatile solids)	%TS	92.00	–
Density	kg/m^3	400.56	–
C	%	–	39.1 ± 0.4
N	%	1.42	3.3 ± 0.2
P	%	0.28	1.1 ± 0.0
K	%	0.68	1.4 ± 0.0
Ca	%	1.44	4.8 ± 0.6
Mg	%	0.28	0.8 ± 0.1
Na	%	0.27	–
S	%	0.50	1.0 ± 0.0
Cu; Zn; Mn; Fe; B	ppm	99.33; 98.67; 929.33; 27.83	–
C/N[a]	–	36.70	–
Ash	%	–	13.7 ± 0.1
Extractives	%	–	11.7 ± 0.1
Cellulose (Glucose)		35.7 ± 1.4	23.6 ± 0.3
Hemicelluloses (Galactose, Arabinose, Xylose, Mannose)	%	9.2 ± 1.0	17.5 ± 0.5
Acid soluble lignin	%	–	1.8 ± 0.0
Acid insoluble lignin	%	27.7 ± 0.7	27.6 ± 0.1

fiber remains for the most part intact and undigested after incorporation in typical mesophilic AD units, representing, in its mechanically separated form, approximately 40% of the AD effluent TS [11]. This fiber can be an important raw source for value-added processing and product development. Table 1 presents a summary of some characteristics of AD dairy fiber according to two works. The values suggest that AD characteristics depend on the origin of the material. Although hemicellulose degradation is expected during the AD process, it is seen that an important portion of it remains intact. Nitrogen content in AD dairy fiber is high when compared with other lignocellulosic materials such as wood.

Pretreatment through various biological, chemical, mechanical, and thermal methods [13–15], and subsequent incorporation of the fiber for a second run at the AD process could allow for greater access to its biogas potential. For example, Biswas et al. [16] reported that a wet explosion process, calculated in conjunction with known US AD and fiber operational data, could increase AD methane production by up to 41%. While an impressive increase in gas productivity as well as potential electrical or CNG sales, net revenues resulting from the pretreatment costs and extra biogas should be compared to other value-added uses for the digested fiber. Recognizing this pretreatment pathway as a viable route (especially if value of the produced biogas and final energy/fuel product increases) is of merit but in addition, continuing down the alternate path of obtaining value to the existing AD fiber appears as a promising pathway for complete use of the fiber and for providing dairy farmers with strategies to increase revenues.

Although recent works [17,18] review some options for adding value to AD agricultural and food waste, there is a lack of works focusing on AD dairy fiber. The objective of this paper is to summarize the literature regarding numerous existing and potential value-added uses for AD dairy fiber. Some discussions rely on processing and use of the non-digested fiber fraction or the whole dairy manure. It is expected that the review will provide information to those interested in planning strategies for adding value to AD dairy fiber.

2. AD fiber for bedding/soil amendment/peat replacement

2.1. Manure and/or AD fiber as feedstock for dairy bedding and soil amendments

Bedding for cows remains a common first choice for using the separated AD fiber [19,20]. From a mass balance perspective, a WCE produces approximately 7–9 m^3/year of wet digested fiber (70–75% moisture content–MC) from the back end of the digester and liquid/solids separation [11]. Simple mechanical screens with scale variable capital ($45–80 per cow) and operating ($8–16 per cow per year) costs can effectively separate the fiber from the manure and/or wastewater [21]. The digestion process both reduces pathogens (2–3 log reduction) [11] and stabilizes the organic carbon in the effluent fiber, yielding a product that currently represents approximately 300,000 WCE in the US [22]. Typical revenues calculated from offset savings of not purchasing and using sawdust, straw, or other materials for bedding are on the order of $6–8 per wet m^3 ($21–27 per wet t), although in some states and regions with high feedstock costs this range could be higher [23]. Farm mass balances show an approximate internal need for 50% of the produced fiber while the remaining 50% could be used for other value-added processing or sold as bedding to nearby dairies without a digester [11]. Several companies have entered the marketplace with additional treatment and drying technologies that further prepare the digested or even non-digested fiber for use as animal bedding. These, among others, include Eco-Composites (Holland, MI), who through a patented drying and treatment process, produces a Perfect Cycle® Natural Bedding that is sold in pelletized form to regional dairies, rabbit breeders and horse stables [24,25] and Nutrient Control Systems (Chambersburg, PA) who selectively target longer fiber particles from non-digested, separated fibrous solids and treats them in short-cycle in-vessel composters.

After separation, another common method to add value to AD fiber is to apply basic compost processing methods—adding aeration and space under controlled conditions for sufficient time to compost the fiber [20]. As part of the AD process, carbon is partially converted into methane, thus AD fiber can have carbon to nitrogen ratios lower than raw manure, but still within the range and with the necessary moisture content for successful composting, especially if the fiber is co-composted with other materials to obtain even more advantageous carbon to nitrogen ratios and other compost properties [26]. While AD fiber may already have reduced pathogen content, hot composting practices can give additional assurance of pathogen reduction and prevent regrowth of pathogens during storage [26]. Composting stabilizes the carbon and other nutrients in the fiber material, darkening the fiber, making it look more like soil. It also reduces the volume and can drive off some of the moisture, producing a product that is easier to handle and with less weight. After composting, the darker composted fiber can be marketed for higher value, either alone or as a desirable ingredient in blended nursery and garden soil mixes [10,26,27]. Typical price points for bulk sales of composted dairy manure/fiber containing appreciable concentrations of nitrogen (~15 kg N/t) are around $20/t with an additional $10/t charge for large-scale field application [28].

A more specialized form of composting with practical application using composted whole dairy manure and/or dairy fiber is vermicomposting [29,30]. Vermicompost is a process in which specialized worms are grown in the presence of organic residuals using a variety of continuous production systems, such as low-cost floor beds, containers or boxes, and raised gantry-fed beds, for production of a greater population of earthworms (e.g., animal or fish protein) or for production of earthworm castings or vermicompost [30]. Research has established the favorable conditions for using earthworms to process cattle or dairy manure solids, as well as bio-solids resulting from AD of wastewater [30]. The earthworms fragment and consume the fibrous organic matter obtaining nutrition from the microorganisms that grow on the feedstock [29].

2.2. AD fiber as a component of growth substrates used in container plant production systems

Greenhouse and nursery production of high-value crop plants is a specialized segment of the horticulture industry. Both woody and