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Digestate liquor recycle in minimal nutrients-supplemented anaerobic digestion of wheat straw

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ABSTRACT

Anaerobic digestion (AD) of minimal nutrient-supplemented wheat straw and digestate liquor recycle was evaluated in semi-continuous processes using a novel BioReactor Simulator developed for easy accurate online normalised-gas measurement. Three scenarios (i) no recycle (NR), (ii) recycle of soluble nutrient (RSN), and (iii) recycle of nutrient and microbes (RNM) were investigated in order to evaluate their respective efficiencies. Although mono-digestion of lignocellulosic biomasses are often performed with very long solid retention times (SRT), the present study demonstrated an efficient process operating with a 30-day SRT and an organic loading rate of 4 g VS/L d. The best methane yield was 303 mLCH_4/g VS achieved in the RSN process showing a 21% improvement as compared to the NR process. The methanogenic potential of the digestates from the RSN and RNM processes was comparable to fresh inoculum indicating efficient processes. The RNM and RSN processes showed superior process stability evidenced by minimal volatile fatty acid accumulation (<0.5 g/L). As compared to the RNM process, RSN demonstrated the best performance. The improved process performance was probably due to higher nutrient and microbial concentration in the digestate-recycled processes. This study confirms the feasibility of digestate recycle in AD as an appropriate technology for treating nutrient-deficient substrates.

1. Introduction

Megatons of wheat straw are produced globally each year. In 2010, world wheat production reached 651 million tons and assuming a residue to crop ratio of 1:3, wheat straw production can be estimated at 846 million tons [1]. Wheat straw is, therefore, an abundant, generally regarded as cheap and accessible agricultural residue that can be use for biogas production [2,3]. Biogas production via anaerobic digestion (AD) has gained increasing attention in recent years as it can act both as waste treatment and generation of a renewable energy carrier in the form of methane (biogas). Indeed, biogas can be used for heat and power generation, injected into the national gas grid, or it can be upgraded and used as vehicle fuel. Biogas could, therefore, partially replace fossil-based fuels thereby, mitigating environmental problems such as green house gas-emission and global warming [3,4].

Research on biogas production from wheat straw has been reported in literature before [5–7]. However, AD of wheat straw has primarily been limited by its slow hydrolysis [8]. An explanation to this is that wheat straw is lignocellulosic in nature, wherein cellulose and hemicelluloses (holocellulose) are tightly covered by a network of hydrophobic lignin [9]. However, many pre-treatment studies have been addressed towards an improvement of the anaerobic biodegradability of straw [10–12]. Another important drawback of the AD of wheat straw is its poor content of both micro-and macronutrients. Nutrients are needed by anaerobic microorganisms for physiological and enzymatic reactions [13–15]. In fact, it has been demonstrated that the hydrolysis as well as nutrient deficiency were the main causes of poor process-performance of the AD of straw [16].

Many studies on both macro and micronutrient supplementation have been performed with the goal to improve the performance and stability of the AD process [15,17]. In such studies, relatively high amounts of nutrients are often added to the processes [13,15,16]. However, it will be desirable to limit nutrient supplementation in an AD process, especially with regards to

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Abbreviations: AD, anaerobic digestion; AMPTS, automatic methane potential test system; BMP, biochemical methane potential; IP, inoculating potential; NR, no recycling; OLR, organic loading rate; RMN, recycling of nutrients and microbes; RMP, residual methane potential; RSN, recycling of soluble nutrients; SRT, solid retention time; TS, total solids; VS, volatile solids; WW, wet weight.

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the upcoming global shortages of natural resources such as nickel (Ni), cobalt (Co), phosphorous (P) etc. [18,19]. There is, therefore, a need to develop straw-based minimal nutrient-supplemented AD processes with high performance and sustained stability. Minimal nutrient-supplementation for improved AD processes will also be economically viable, as it will go a long way to reduce operational cost. In addition, most reported literature on AD of wheat straw are based on a two-stage digestion configuration wherein a hydrolytic first-step is coupled, and where after the leachate is fed into a second stage high-rate reactor such as the upflow anaerobic sludge-blanket (UASB) [7,20]. However, these sophisticated two-stage systems has limited their application [21]. On the other hand, most commercial biogas plants in Europe, especially in Germany, which is the trailblazer in biogas production, are operated in continuous stirred-tank reactors (CSTR) [22]. It is, therefore, vital to promulgate straw-based CSTR biogas-studies especially as the CSTR is practical, easy to operate, based on established technology, and as it has been successfully employed for AD of various solid wastes [23,24].

The hypothesis investigated in the present study was that the performance of wheat-straw (supplemented with minimal amounts of nutrients) based AD in CSTRs can be improved by recycling of digestate or effluent liquor back into the reactors. The study was performed at a relatively short solid retention time (SRT) of 30 days considering the very long SRTs (170 days) usually applied in mono-digestion of lignocellulosic biomass [22,25]. Three scenarios were adopted and compared: (i) without recycling of digestate serving as a reference or control to (ii) recycling of supernatant after centrifugation, and (iii) recycling of permeate after filtration. The study was conducted with the aid of a BioReactor Simulator or BRS (Bioprocess Control, Lund, Sweden) which were 15-L stainless steel-reactors supported by web-based software for on-line, real-time process monitoring and data-acquisition system enabling fast, accurate, and easy normalised-biogas measurements. The biochemical methane potential (BMP) of the wheat straw, the residual methane potential (RMP), and the inoculating potential (IP) or methanogenic activity of the digestates were also assessed in batch assays. Often, the digestate from an active biogas process is used as inoculums, here; we are for the first time investigating the liaison between the IP and the process performance.

2. Materials and methods

2.1. Substrate and inoculums

The substrate was pre-dried wheat straw obtained from an animal store (Zoobutik, Malmö, Sweden), milled to <3 mm with the aid of a homogenizer (Grindomix 200, Retsch, Germany). During feedstock preparation, tap water, micro- and macro-nutrient solution (see Section 2.1.1), or digestate liquors from the AD processes were used to dilute the milled wheat straw. Procedures for managing the different digestate-fractions (liquor) are discussed in Section 2.2.2.

Inoculum was collected from an active mesophilic biogas-plant (VAsyd, Ellinge, Sweden) treating municipal sewage-sludge. Characteristics of substrates and inoculum are presented in Table 1.

2.1.1. Nutrient addition

Concentrated stock-solution of macronutrients i.e., nitrogen (N), phosphorous (P), and sulphur (S) was prepared and added to the substrate during feedstock preparation. N, P, and S were provided by 56.4 g/L ammonium hydrogen carbonate (NH_4HCO_3) which also provided buffering, 25.7 g/L urea ($CO(NH_2)_2$) a cheap N source and 16.5 g/L ammonium sulphate ($(NH_4)_2SO_4$), which also provided S and 16–22.9 g/L sodium hydrogen phosphate ($NaH_2PO4 \cdot 2H_2O$). Concentrated stock-solutions of micronutrients were prepared and added to the feedstock to provide iron (Fe), cobalt (Co), nickel (Ni), molybdenum (Mo), and wolfram (W) in the form of 5.33–8.88 g/L iron chloride ($FeCl_3 \cdot 4H_2O$), 0.11–0.36 g/L cobalt chloride ($CoCl_2 \cdot 6H_2O$), 0.09–0.24 g/L nickel nitrate ($Ni(NO_3)_2$), 0.64–1.26 g/L ammonium molybdate ($(NH_4)_6Mo_7O_{24} \cdot 4H_2O$), and 0.07–0.18 g/L tungstic acid sodium salt dihydrate ($Na_2WO_4 \cdot 2H_2O$) respectively. Levels of nutrient additions were decreased with increasing OLR (Table 2). All chemicals were of reagent grade (Savern and Werner, Sweden). Micro and macronutrients, and their concentrations added to the feedstock are presented in Table 2. N was added in feedstock to reach a C/N ratio between 20 and 30 [25]. Added concentrations of P and S were 4 times less than recommendations from previous studies [15,16]. Chosen concentrations of micronutrients were lower (up to 11 times) than those previously reported to elicit high methane-yields and process stability in AD of lignocellulose-based biomass [13]. However, the concentrations were higher than the minimum requirements for the AD of pure substrates such as glucose and acetate under mesophilic conditions [14].

2.2. Process operation

2.2.1. Biochemical methane potential of wheat straw, residual methane production, and inoculating potential of the digestates

The specific methane yield or BMP of wheat straw, RMP, and the IP of the respective digestates were studied in batch assays using the automatic methane potential test system or AMPTS II (Bioprocess Control AB, Sweden). For the BMP, tests were conducted in triplicates, under mesophilic conditions, and the inoculum to

Table 1

Characteristics of wheat straw and inoculums used in the experiment wherein nutrients concentration as given in mg/kg wet weight (WW) and mg/kg VS.

	Wheat straw		Inoculum	
TS (%)	95.6 ± 2.1		2.8 ± 0.2	
VS (%)	88.3 ± 0.9		2.0 ± 0.1	
	mg/kg WW	mg/kg VS	mg/kg WW	mg/kg VS
C	447000 ± 4920	506229 ± 5572	8130 ± 976	406500 ± 48800
N	8120 ± 521	9156 ± 570	1620 ± 178	81000 ± 3900
P	800 ± 32	906 ± 36	380 ± 17	19000 ± 850
S	540 ± 23	612 ± 26	340 ± 15	17000 ± 750
Fe	84 ± 13	95 ± 15	140 ± 9	7000 ± 450
Ni	0.41 ± 0.003	0.46 ± 0.003	0.86 ± 0.05	43 ± 2.5
Mo	0.20 ± 0.001	0.23 ± 0.001	0.27 ± 0.009	13.5 ± 0.45
Co	0.20 ± 0.003	0.23 ± 0.001	0.05 ± 0.001	2.5 ± 0.05
W	1.0 ± 0.06	1.13 ± 0.07	1.20 ± 0.07	60 ± 3.5
Ca	2500 ± 180	2833 ± 204	340 ± 24	17000 ± 1200
K	3600 ± 201	4077 ± 228	690 ± 61	34500 ± 3050