Recent Progress on Dry Anaerobic Digestion of Organic Solid Wastes: Achievements and Challenges

Zhongfang Lei*, Zhenya Zhang, Weiwei Huang and Wei Cai

Graduate School of Life and Environmental Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8572, Japan

* Corresponding author. Graduate School of Life and Environmental Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8572, Japan. Tel/fax.: +81 29 853 6703, +81 29 853 4712.
E-mail address: lei.zhongfang.gu@u.tsukuba.ac.jp (Z. Lei)

Abstract: Recent works on dry anaerobic digestion (AD) show that not only methane but also hydrogen, volatile fatty acids (VFAs), and ethanol can be produced from municipal solid waste (MSW), dewatered sewage sludge, animal manure or crop residue by dry AD processes. Up to now only methane production from household wastes has already been commercialized by using dry AD technology. Single-stage dry AD processes with semi-continuous or continuous operation mode dominates the commercialized dry AD plants. To get enhanced biogasification efficiency, naturally microbial pretreatment methods (like stack-pretreatment and aerobic or facultative composting) and co-digestion are practically useful for dry AD, especially for the treatment of carbon- and nitrogen-rich organic solid wastes, *i.e.* crop residue and animal manure. Dry AD could achieve comparable production efficiency to wet AD systems, yielding 121 - 340 L of CH_4 from per gram volatile solids (VS) of organic fraction of MSW (OFMSW) and 51 - 55 ml H_2/g-$VS_{reduced}$ from OFMSW, sewage sludge, and paper and food wastes. Still, future researches are necessary and demanding for dry AD to better challenge with other low-cost treatment and disposal methods, which are also proposed in this review mainly relating with its longer solids retention time, feedstocks collection, inhibitory substances, online process monitoring, and establishment of process assessment index system.

Keywords: Dry anaerobic digestion, municipal solid waste, sewage sludge, animal manure, crop residue, methane, hydrogen, volatile fatty acids

INTRODUCTION

Anaerobic digestion (AD) or anaerobic fermentation, a low-cost treatment, has been widely applied for biological conversion of organic solid waste or wastewater into renewable energy. This biotechnology is attracting more and more interests not only due to its simultaneous pollution control and recovery of renewable energy, but also the depletion of fossil fuel reserves and the rising price of energy.

The biological processes involved in AD include the following four distinctive steps. (1) Hydrolysis is the first step, in which large polymers or particulate matters are broken down by enzymes into smaller or soluble substances. (2) Fermentation, especially acidogenic fermentation, is the most important step with acetate as the main end product. During this process volatile fatty acids (VFAs) are generated along with CO_2 and H_2. (3) Acetogenesis follows the above two steps, during which volatile acids are broken down into acetate and H_2. (4) Methanogenesis: the generated acetate, formaldehyde, H_2 and CO_2 are converted into methane and water.

According to the solids content in the fermentation substrate, AD can be classified as wet, semi-dry, and dry AD processes. Conventional wet AD requires: (1) to supply and handle large volume of external water; (2) to install large reactors; (3) to cope with the dewatering of large volume of digester effluents; and (4) to provide a large amount of energy for digester heating, feed slurry pumping, and effluent dewatering and disposal [1]. The above-mentioned disadvantages, especially the substantial increase in the volume of treated waste (digestate, digester effluent, or fermentation liquor) makes the conventional wet process uneconomical. Sometimes semi-dry AD achieves inefficient results when dealing with high solid wastes. In the case of feedstocks with high solids content, dry AD can be applied, which shows very high rates of biogas production for per unit reactor volume [1].

Dry AD technology is attracting more interests because of its less pretreatment requirement and water consumption compared with wet processes [2], enabling a higher volumetric organic loading rate, higher biogasification performance, smaller reactor capacity requirement, less energy used for heating, and easier handleability of digestate [1-3]. Up to now, no clear difference in solids content has been used for wet and dry AD. Sometimes dry AD means solids content > 15%, while the solids content in wet AD ranges between 0.5 - 15% [3]. Sometimes total solids (TS) of 20 - 40% or 20 - 25% are classified as dry AD [1, 2], while sometimes dry AD also refers to TS = 20 - 55% [4] or 20 - 35% [5].

According to De Baere and Mattheeuws [6], the cumulative percentage of dry AD capacity installed in Europe in 2014 is about 62% for the treatment of municipal solid wastes (MSW), much higher than wet fermentation (38%). Besides MSW, dry AD has been found to have great potential for the treatment of animal manure and sewage sludge. Recently Deng *et al*. [7] tested the effect of separating swine manure into different concentration fractions on biogas production. Their results showed that higher solid contents of swine manure had higher recovery rate of organic matter, resulting in elevated digestion temperature and faster degradation rate with improved biogasification efficiency of the entire system especially in winter. After conducting dry AD on sewage sludge, Duan *et al*. [8] claimed that high solids AD could achieve higher organic loading rates (OLR) and longer solids retention time (SRT), leading to higher volatile solids (VS) reduction and methane yield. In addition, they also found that the high solids system had better performance under lower free ammonia nitrogen (FAN) conditions. Restated, all the recent publications direct that dry AD is a promising biotechnology with high efficiency recovery of bioenergy and other products from organic solid wastes. Up to now there are a few reviews available on dry AD. Li *et al*. [3] addressed the principles and applications of solid-state methane production from organic waste. Kothari *et al*. [9] reviewed the fundamental aspects including reactions, microbial species, effect of feedstocks and operation parameters along with reactor types of dry AD process. In addition, the inhibition factors involved in AD [10], enhanced methane production by using pretreatment techniques [11-14], and co-digestion achievements [15] have been also summarized. Most of the above mentioned reviews are mainly associated with wet AD except Li *et al*. [6] and Kothari *et al*. [9], from which limited information could be obtained on recent progress of dry AD not only for methane production but also for other bio-products like hydrogen and VFAs production. Therefore, this review summarized the recent works on raw materials used for dry AD, including various bio-products from dry AD, operational conditions for batch and continuous dry AD reactors in addition to their enhancement strategies. The challenges of dry AD in practical application were further discussed, with an expectation of accelerating its utilization and commercialization in the treatment and recycling of various organic solid wastes.

RECENT RAW MATERIALS USED IN DRY AD FOR THE PRODUCTION OF VALUABLE BIOPRODUCTS

Besides food wastes, agricultural wastes, and organic fraction of municipal solid waste (OFMSW) being used [3], various other kinds of organic wastes have also been tested for dry AD, such as dewatered sewage sludge or its co-digestion with food wastes [8, 16], textile-processing residue or willow-dust [17], wetland residue, *Spartina alterniflora* [18], falling leaves [4], energy crops like *Sorghum* and *Sorghum*/cellulose mixtures [19], animal manure or its co-digestion with food wastes [7, 20-26].

Generally, dry AD has been applied to produce methane as final energy source in most of the research works (Table **1**). Still, it is also found that the above-mentioned feedstocks can be used in dry

AD for the production of hydrogen [16, 20, 27], VFAs [28, 29], and ethanol [30]. In addition, bioflocculants can be further generated by using the fermentation liquor from the dry AD process of rice straw [31].

As shown in Table **1**, the methane production varied among the various feedstocks and different operational conditions of dry AD. MSW, especially OFMSW shows a high stability in methane production by using dry AD, with resultant methane yield ranging from 121 to 340 L/kg-VS when solid retention time (SRT) was changed from 35 to 8 days under thermophilic dry AD at TS = 20 - 30% [5, 38, 70]. Furthermore, OFMSW, sewage sludge, and paper and food wastes can be used for H_2 production, yielding about 51 - 55 ml H_2/g-$VS_{reduced}$ under thermophilic dry AD with proper inoculation [16, 27]. Ethanol and VFAs may be another two promising products from lignocellulosic materials like corn stover and oil palm residue by dry AD technology [29, 30]. These experiments show that longer SRT is necessary for dry AD to achieve an effective decomposition and utilization of lignocellulosic materials.

It is clearly seen that dry AD could achieve similar or comparable biogas and methane yields and VS reduction effect with wet systems under controlled operational conditions. Meanwhile, dry AD can be operated under higher organic loading rates (OLRs, about 4 - 6 times higher) than wet systems, thus achieving much higher volumetric production rate and higher energy recovery [8, 32, 33].

Table 1. Recent major achievements and rising problems in dry AD experiments for various bio-products

Feedstock	Major bio-product	Experimental conditions	Major achievements and problems	Ref.
Dewatered sewage sludge	Methane	1) Single-stage and helix-type CSTR 2) Temperature=35±1℃ 3) TS=19-23% 4) OLR increased stepwise from 2.0 to 4.1 kg VS/(m^3·d)	1) Under 20% TS (VS/TS =60%) of feedstock, OLR 2.0-3.0 kg VS/(m^3·d), and SRT=40-59d conditions, VS reduction of 39-40% and methane yield of 0.22-0.24 l CH_4/(g-VS_{added} d) were achieved. 2) No evident influence was found when FAN<250 mg/L and VFA < 400mg/L; slight inhibition occurred at FAN=250-400 mg/L and VFA=400-800 mg/L; FAN=400-600 mg/L and VFA=1000-3000 mg/L, and FAN=600-800 mg/L and VFA=3000-4500 mg/L caused moderate inhibition and significant inhibition, respectively. 3) High solids systems achieved similar methane yields and VS reduction with 4-6 times higher OLR as the conventional system did, thus much higher volumetric methane production rate. 4) Both FAN and VFAs concentrations influenced methanogenic activity in dry AD systems, and VFAs/TA ratio was not suitable to be used for the assessment on system instability.	[8]
Food waste, fruit and vegetable waste, leaf waste and office paper	Methane	1) 0.55 m^3 continuously operated inclined thermophilic dry anaerobic digester 2) TS=15-25%, 55℃ 3) C/N=27-32, OLR =0.65 to 10.7 kg VS/(m^3 d) 4) Partial or completely mixing mode 5) Inoculatoin with a mixture of cow dung, anaerobic digested food waste and brewery sludge from the UASB of a beer factory.	1) The minimum and maximum specific methane yields were 121 and 327 L/kg-VS_{added} at FAN about 164 and 284 mg/L (TAN=1895 and 2671 mg/L), and VFAs/TA of 0.35 and 0.51, respectively. 2) Accumulation of both ammonia-N and free ammonia was not directly associated with the accumulation of VFAs. 3) The adverse effect of ammonia inhibition was reduced when shorter SRT, higher feed C/N ratio and higher OLR applied with decreased protein solubilization rate and hence less ammonia-N accumulation in the reactor. 4) The decentralized system (ITDAD) achieved enhanced energy production by 50-73%, which is more economically feasible than the centralized systems.	[32]

Food waste co-digested with paper waste or livestock waste	Methane	1) 60 L horizontal-type cylindrical reactor agitated at 25 rpm 2) Continuously mesophilic digestion (30-40℃) 3) TS=30-50%, HRT=100-30 day, solid loading rate increased from 2.0 to 10.0 kg TS/(m^3·d) 4) Seed: dewatered sludge cake	1) At HRT=40 d and TS=40%, biogas production rate, CH_4 yield and VS reduction achieved were 5.0 m^3/(m^3·d), 0.25 m^3 CH_4/g-COD_{added}, and 80% when co-digested with paper waste. 2) At 40% livestock waste content, the reactor stabilized at a biogas production rate of 1.7 m^3/(m^3·d), methane yield of 0.26 m^3 CH_4/g-COD_{added}, and VS reduction of 72%. 3) The performance was comparable to conventional wet digestion and thermophilic dry AD processes. 4) Further shorten HRT to 30 d resulted in the inhibition of solids hydrolysis. 5) Ammonia inhibition to microorganisms occurred when livestock waste was used as co-substrate (FAN~1000 N/L, TAN=2000-7000 mg-N/L)	[25]
OFMSW	Methane	1) 5L semi-continuously CSTR operated at thermophilic single-stage 2) TS=20-30% and SRT varied from 15 to 3 days 3) Inoculum from a thermophilic stable reactor treating OFMSW	1) Progressive decreasing of SRT could achieve stable conditions for shorter SRT. 2) The best conditions were determined to be SRT=5-8 days with methane yield of 0.33-0.34 L CH_4/g-VS_{added} and VFAs around 100 mg HAc/L. 3) SRT < 4 days was not suitable for single-stage dry AD of OFMSW with methane yield lower than 0.2 L CH_4/g-VS_{added} and an accumulation of VFA > 500 mg HAc/L.	[5]
OFMSW	Methane	1) 5L semi-continuously fed CSTR by using modified SEBAC reactor 2) Thermophilic (55℃) at TS=30% and pH=6.5-8 3) Inoculation with a mixture of leachate and sludge from the modified SEBAC	1) Remarkable reduction in the start-up and stabilization period: 110 days in comparison to 250 days for other processes. 2) Maximum biogas production of 1.944 L/(L·d), 530 ml/g-VS, 121ml CH_4/g-VS with average CH_4 about 40% were achieved at SRT=35 d. 3) Maximum percentages of VS (88%), TS (58%) and DOC (64%) removals were obtained under OLR of 7 kg VS/(m^3·d) and SRT=25 d.	[34]
Chicken manure		1) 125ml serum vials 2) TS=25% 3) Temperature= 37, 55 and 65℃	1) A total volume of 4.4 l /kg-CM (31 ml /g-VS) of methane was produced under high level of ammonia of ca. 8 to 14 g-N /kg-CM at 37℃ after a long lag phase period (254 days). 2) Acclimatization was not observed at both 55 and 65℃, attributable to their higher ammonia	[23]

		4) Inoculated with anaerobic sludge	levels than that at 37℃. 3) Spontaneous acclimation of the methanogenic consortia to high levels of ammonia could occur, resulting in methane production even under a high percentage of TS (25%) and a high level of ammonia.	
Manure or co-digested with food waste or sewage sludge	Methane	1) 1.0L batch digesters with inocula from biogas plant 2) TS=11-31% 3) Anaerobic digestion at mesophilic and thermophilic conditions	1) The BMP of digestate was 156-240 L CH_4/kg-VS, similar to the BMP of untreated cattle slurry. 2) The estimated gravimetric BMP, 15-49 L CH_4 /kg was much higher than that from untreated animal slurry. 3) Concentrated digestate re-circulating was promising for digesters to obtain increased biogas yield and stable digestion process.	[26]
Swine manure	Methane	1) Semi-dry AD trials after sedimentation separation: 1000 ml glass flasks, 2.27 kgCOD/(L ·d), 35℃ by using semi-continuous mode 2) Inocula from anaerobic digester treating swine manure	1) Sedimentation separation could recover 85% of solids from raw swine manure in high solids liquid portion. 2) The high solids liquid (TS~5%) with 30% less volume of the raw slurry contained 52.7-70.6% of COD and 57.6-80.1% of BOD_5 generated increased biogas yield by 75%. 3) The high solids content liquid had 2.48-5.42 times higher COD content and 2.81-5.92 times higher BOD_5 than the raw slurry with a faster degradation rate. 4) Increasing TS concentration in the substrate may enhance the energy efficiency of the whole system.	[7]
Horse manure (straw-based)	Methane	1)Single-stage: 27.36L; two-stage: 27.36L+21.26L 2)Reactor: UASS process with liquor recirculation. 3)Methophilic (37℃)and thermophilic (55℃) 4)TS=20-26%	1) Thermophilic UASS process had a significantly higher efficiency than mesophilic process with an increase of 59.8% in CH_4 yield and 58.1% in CH_4 production rate. 2) Single-stage and two-stage processes showed no obvious difference in biogasification performance. 3) Average CH_4 production at 55 ℃ was enhanced from 0.387 to 0.687 L/(L·d) with the increase in organic loading from 2.5 to 5.5 g VS/(L·d), resulting in CH_4 yield decreased from 154.8 to 124.8 L/kg-VS.	[21,22]
Municipal	Methane	1) 40 L lab scale complete mixing	1) Biogas and methane production were similar, around 200 m^3CH_4STP/t-VS.	[35]

solid waste		and 21 m^3 pilot-scale reactors 2) Mesophilic and thermophilic 3) TS=35±3% 4) Initial inoculation ratio=35% (w/w)	2) The lab-scale reactor could exactly mimic the pilot-scale reactor. 3) Ammonia concentration varying from 1200 to 2000 mg N/L didn't seem to be high enough to bring about the inhibition. 4) A temporary VFAs accumulation was subsequently followed by their degradation. 5) Microorganisms' Adaptation to the waste and operation conditions was important. 6) Few in-line measurement is available for dry anaerobic process.	
Municipal sorted biowaste	Methane	1) 3L Box-type glass reactor 2) TS=20%, 25%, 30% 3) Temperature=20, 37, 55℃ 4) Re-feeding: 1 kg digestion residue was mixed with 1 kg fresh biowaste	1) Almost same digestion efficiencies as for wet anaerobic digestion (completely mixed reactor) of biowaste were obtained for dry AD with TS=20% at 20, 37 and 55℃ and with TS=25% at 37 and 55℃: 0.53-0.59 m^3/kg-organic biowaste, methane content of 70-75%, HRT=60d. 2) Population densities in 20-30% TS biowaste reactors were similar, although remarkably less but phylogenetically more diverse archaea were co-existing in the mesophilic and thermophilic biowaste reactors at 30%TS. 3) Little methane was detected in dry AD reactors with TS of 30% at 20, 37 or 55℃.	[33]
Fallen leaves	Methane	1) 1L glass reactor, 2) TS=20%, 37℃ without agitation 3) NaOH dosage=2-5% with inoculums	1) The highest methane yield, 82 L/kg-VS, was achieved at NaOH loading of 3.5% and substrate-to-inoculum (S/I) ratio of 4.1. 2) The greatest enhanced methane production was achieved at S/I ratio of 6.2 (C/N=22) with NaOH loading of 3.5%, about 24-fold higher than the control (no NaOH addition). 3) Final total VFAs/TA ratios of all healthy reactors were below 1.6, higher than the limit of 0.6 for wet digestion. 4) Increasing in TS content from 20% to 26% resulted in decreased biogasification. 5) The highest cellulose and hemicellulose degradation, about 36.0% 34.9% respectively, were obtained at 3.5% NaOH loading, highly co-related with the methane yields.	[4]
Spartina alterniflora	Methane	1) Three 6 L leaching bed reactors (LBRs) and six 1 L batch reactors 2) 55℃with TS=17.9-21.5% 3) Thermo-lime pretreatment with	1) Hot-water pretreated samples produced much higher biogas yield (206.8 ml/g-TS) with larger production rate constant (k, 0.052 d^{-1}) than those of the thermo-lime-pretreated samples (168.3 ml/g-TS and 0.028 d^{-1}), the former produced higher VFAs. 2) TS content decreased from 20.8% to 17.9% led to 29.6% increase in biogas yield and 67.9%	[18]

		0.09 g $Ca(OH)_2$/g- TS or hot water at 120℃ for 4 h	in production rate constant (k) values. 3) Lignin content increased while cellulose and hemi-cellulose contents decreased in *Spartina alterniflora* after dry AD. 4) Enhanced process stability was achieved at lower TS conditions.	
OFMSW co-digested with sewage sludge	Hydrogen	1) Batch assays, 250 ml serum bottles 2) 55℃, TS=10-25% 3) Initial pH=5.5 4) Inoculums from lab-scale anaerobic reactor treating OFMSW	1) Co-digestion of OFMSW with sewage sludge resulted in 70% increase in H_2 production compared to OFMSW fermentation only. 2) Mixture sludge was the best co-substrate compared with primary sludge and wasted activated sludge. 3) Maximum H_2 yield of 51 ml H_2/g-$VS_{consumed}$ at 20%TS and OFMSW/mixed sludge=5:1. 4) Acetic and butyric acids were the main VFAs (73-79%), and H_2 fermentation was butyrate type fermentation. 5) Co-digestion with sewage sludge which supplied N element not only enhanced H_2 production, but also accelerated the fermentation process.	[16]
Paper and food wastes	Hydrogen	1) 1.0 L glass jars operated in draw-and-fill mode with 21-35% TS at 55℃ 2) Using phosphate buffer solution (pH7.21) 3) Inocula from dry anaerobic methane fermentor.	1) High TS and alkalinity ratio had adverse effects on H_2 productivity and H_2 yield, which significantly increased when TS content and alkalinity ratio decreased. 2) The highest H_2 productivity and yield, 463.7 ml/(kg d) and 54.8 ml/g-$VS_{removed}$ respectively, were produced at 20.9% TS and alkalinity ratio of 0.25 (0.11 g $CaCO_3$/g-dry substrate) 3) The adverse effect of excessive alkalinity might be brought about by the resultant increased osmotic pressure	[27]
Corn stover	Ethanol & Methane	1) Pretreatment: steam-exploded at 2.0 MPa for 5 min 2) Ethanol production: 2L at TS=35.5%, started by enzyme addition and prehydrolysis for 6 h at 50℃ and 150 rpm, then	1) A 69.8 g/kg-mass weight (72.5%) of ethanol titer was obtained when the process was operated in batch mode at solids loading of 35.5% (w/w). 2) Maximum cellulose conversion was 80%. 3) A methane productivity of 320 ml CH_4/g-VS and a maximum VS reduction efficiency of 55.3% were achieved during the single-stage digestion for 52 days. 4) Overall product yield was calculated as 197 g ethanol + 96 g methane/kg-corn stover.	[30]

		temperature decreased to 35℃ with the yeast *Saccharomyces cerevisiae* being inoculated. 3) Methane production of the stillage from ethanol production: 3L at 17.5%TS and 35℃	5) The combined process can promote the overall substrate utilization, especially for lignocellulosic materials compared to single ethanol fermentation process.	
Oil palm lignocellulosic residue co-digested with pig manure	VFAs	1) Pretreatment: steam cooked at 140℃ for 15min and subsequently mechanical threshing to release the fruits, then dried at 60℃ and reduced in size to 5 cm. 2) ALBR: 40 L operated by cyclic flooding and flushing in batch-wise at 21-25%TS 3) Inoculum: cow manure	1) Addition of pig manure promoted hydrolysis and acidification due to a more biodegradable and hydrolyzable nature of pig manure after releasing organic acids, and nutrients. 2) The highest hydrolysis yield and acidification yield obtained at pig manure: oil palm residue of 50%/50% were 27.9 ±0.3% and 51.7 ±2.6%, respectively. 3) Longer flushing interval prolonged the dry condition, yielding enhanced hydrolytic reaction.	[29]
Rice straw	VFAs and bioflocculant	1) 12 L 2) 20%TS and batch mode at 30℃ 3) Inoculation with biogas slurry taken from an anaerobic digester of cattle dung	1) Acetic and butyric acids were the major VFAs during the process. 2) A much higher bioflocculant activity was achieved by using the 100-day fermentation liquor than the 50-day one, mainly attributable to its higher reducing sugar content. 3) A cost-effective and highly efficient bioflocculant could be produced by using optimum mixing ratio 1:1 synthetic bioflocculant medium and 100-day fermentation liquor.	[31]

AD, anaerobic digestion; ALBR, anaerobic leach bed reactor; BMP, biochemical methane potential; COD, chemical oxygen demand; CM, chicken manure; CSTR, completely stirred tank reactor; DOC, dissolved organic carbon; DM, dry matter; FAN, free ammonia nitrogen; HAc, acetic acid; HRT, hydraulic retention time; ITDAD, inclined thermophilic dry anaerobic digestion system; LBRs, leaching bed reactors; OFMSW, organic fraction of municipal solid waste; OLR, organic loading rate; SEBAC, sequential batch anaerobic composting; SRT, solids retention time; STP, standard temperature and pressure (273.15 K and 101.325 kPa); TA, total alkalinity; TAN, total ammonia nitrogen; TS, total solids; TVS, total volatile solids; UASB, upflow anaerobic sludge blanket; UASS, Upflow anaerobic solid-state; VFAs, volatile fatty acids; VS, volatile solids

REACTOR TYPES, OPERATION CONDITIONS, AND ENHANCEMENT STRATEGIES FOR DRY AD PROCESSES

Types of Dry AD Reactors

Single-stage, two-stage and multi-stage processes have been applied in the studies of dry AD, which can be operated in batch or continuous mode [3, 9]. Ten years ago, Ghanem *et al*. [36] pointed out that two-stage anaerobic digestion would be rational to treat kitchen food solid waste (KFSW) by dry AD: the first-stage for hydrolysis or solubilization of KFSW, and the second-stage for biogasification from the leachate of the first-stage. The same concept of two-stage reactor has been tried in many works, like sequential batch anaerobic composting (SEBAC) or modified SEBAC [32, 33, 36, 37]. Most recently, Michele *et al.* [38] tested the feasibility of using a two-stage process to treat OFMSW: Dry AD (TS=28-29%) with liquid digestate irrigation was employed as the first-stage for hydrolysis, from which liquid digestate was generated and used for methane production by wet AD in the second-stage. Their results were not desirable under the designed operational conditions, possibly attributable to short SRT and high presence of toxic ammonia. Long-term research is still necessary for the utilization of dry AD to treat various organic solid wastes.

Although two-stage or multi-stage anaerobic process has been reported to have many advantages over single-stage processes, up to now, however, as pointed out by Li *et al*. [3], the successful practices for dry AD are using single-stage processes. In Europe, single-stage dry AD process is estimated to treat about 93% of MSW in 2014 [6].

As mentioned above, on the other hand, dry AD reactors can be operated in batch or continuous mode. Li *et al*. [33] claimed that dry AD is often operated in low-tech box fermentors (garage fermentors) and in high-tech vertical or horizontal stirred tank reactors, while most works are focused on the stirred tank reactors which are believed to have much better mass transfer properties. Since Li *et al*. [3] already summarized the configurations of dry AD reactors, especially the commercialized systems, and Kothari *et al*. [9] described the reactor designs for single-stage and multi-stage dry AD processes, this section focused on the recent progress on the operation modes of dry AD process.

As shown in Table **1**, most of the experimental trials were conducted in lab scale reactors (except one pilot scale in [35]). Among these research works, only 2 and 3 were carried out in continuous and semi-continuous dry AD reactors, respectively, and all the other s were operated in batch mode.

Batch Mode Reactors

Recently anaerobic leach bed reactor (ALBR), the frequently used reactor designed for dry AD of biomass in a batch wise operation, has been successfully applied for VFAs and methane production from animal manure or co-digestion with wood powder [39, 40], grass silage [41, 42], and co-digestion of palm oil empty fruit bunch with pig manure [29]. In an ALBR, because the liquid can percolate through the layer of static biomass bed packed in the reactor, the substrate can be hydrolyzed in a relatively dry environment, thus a small amount of liquid is enough to handle and intensify the hydrolysis process. In addition, the operation of intermittent flooding and flushing the bed can add benefit to allow the bed to be under a semi-dry environment and further enhance the enzymatic activity. Co-digestion and longer dry period favor the enhancement of treatment efficiency, in which the later allows for a longer microbial enzyme reaction thus a better efficiency.

By using ALBR to treat a mixture of dairy manure, anaerobic seed and wood powder/chips, around 25% higher in biogas production can be achieved compared to wet anaerobic digesters [39].

As for commercialized dry AD (Table **2**), batch systems are also successful, like BIOCEL and BEKON systems, most probably due to the modular nature of these simple systems and a low technology requirement in comparison to the more technologically advanced continuous systems.

Continuously Operated Reactors

Continuously stirred tank reactors (CSTRs) have been employed to treat OFMSW. When feedstock TS=25-30%, methane yield, methane content in biogas and VS reduction can be stabilized at 0.30 L CH_4/g-COD, 50% and 80%, respectively [43, 44]. As shown in Table **2**, regarding to treating MSW, semi-continuous and continuous reactors still dominate the commercialized dry AD systems possibly due to the advanced technologies and improved mass transfer properties, achieving the same biogasification performance as in small scale reactors.

More recently, two new continuously operated dry AD reactors with some modifications in reactor structure have also been developed, which exhibited high efficiency of methane production and performance stability in dry anaerobic co-digestion. One of them is the horizontal-type cylindrical reactor proposed by Kim and Oh [25] (Fig. **1**), which can be used for continuous co-digestion of high solids of food waste with paper waste or animal manure. When the reactor was applied to co-digest food waste with paper waste at hydraulic retention time (HRT) of 40 d and 40% of TS under mesophilic conditions, the biogas production rate, CH_4 yield and VS reduction could be 5.0 $m^3/(m^3 \cdot d)$, 0.25 m^3 CH_4/g-COD_{added}, and 80%, respectively (Table **1**). The performance they obtained was comparable to the conventional wet digestion and thermophilic dry AD processes. Another new type of continuously operated reactor is the inclined thermophilic dry anaerobic digestion (ITDAD) system developed by Zeshan *et al*. [32] (Fig. **2**). Their pilot-scale experiments indicate that the maximum specific methane yield was 327 L/kg-COD_{added} at total ammonia nitrogen (TAN) of 1895 mg/L (FAN=164 mg/L), yielding 50 - 73% more energy compared to centralized systems (Table **1**).

Table 2. Commercialized DAD plants starting from 1980s

Technology (Country)	Feedstock	Plants*	Major characteristics	Source
DRANCO, OWS, (Belgium)	Household organic waste	26	1) Single-stage and thermophilic (48-55℃) 2) Vertical dry anaerobic digester with no mixing inside the digester, TS up to 40-45% 3) Achieving biogas production rate up to 10 $m^3/(m^3 \cdot d)$ with methane content of 55% under 18.5 kg $COD/(m^3 \cdot d)$, SRT=15-16 d and TS=31-57% (Averagely 41%)	[2, 6, 45-47]
Axpo **KOMPOGAS** AG, (Switzerland)	Organic wastes	76	1) Continuous-feed, horizontal plug-flow dry anaerobic digester for organic waste with a central low-speed agitator 2) Thermophilic (around 55℃), high TS(~25%) and SRT about 14 days 3) The digestate can be converted into high quality compost after dewatered (KOM+PRESS) and composting	[48, 49]
VALORGA International S.A.S. (France)	Household waste and biowaste	27	1) Semi-continuous, vertical cylinders with horizontal single-stage and plug-flow 2) Mesophilic or thermophilic, SRT=15-20 days, TS=25-35% 3) Methane yield about 210-290 L/kg-VS 4) The digesate can be used as soil conditioner after being dewatered and stored under aerobic condition	[50, 51]
BIOCEL, Orgaworld (the Netherland)	Organic fraction of municipal solid waste	-**	1) Robust batch systems for biogas production with heat-electricity generation (the reactors can work independently with low level of mechanization) 2) Combination of AD with composting: batch mesophilic digestion for 20-21 days, post-composting for 5-6 days (drying and pasteurisation) and then sorting after composting process 3) Completely enclosed, optimal odor control 4) Complete inactivation of plant and animal pathogens, possibly due to high VFAs concentration during the first two weeks	[52, 53]
BEKON Energy Technologies	Organic fraction of	14	1) Batch, single- stage process 2) Low construction, operation and maintenance costs due to compact structure, sophisticated and robust	[54]

GmbH & Co. KG (Germany)	household waste		conveyor technology and absence of preliminary treatment 3) Sustainable utilization hitherto unused materials for energy production with high biogas yield and gas quality 4) High safety and emission standard	
STRABAG Umweltanlagen GmbH (Germany)	Household waste	32	1) LARAN® plug-flow digester and continuous operation (thermo- or mesophilic) 2) High organic loading rate and shorter retention times in contrast to fully mixed digesters 3) Unique wear-resistant STRABAG vacuum discharge system 4) High operating reliability and availability through multiple individually driven and robust agitators with short shafts 5) Flexible selection of different substrates with variable TS up to 50%	[55]

*The number of plants is up to September, 2014. **No information available.

SRT, solids retention time; TS, total solids; VFAs, volatile fatty acids; VS, volatile solids

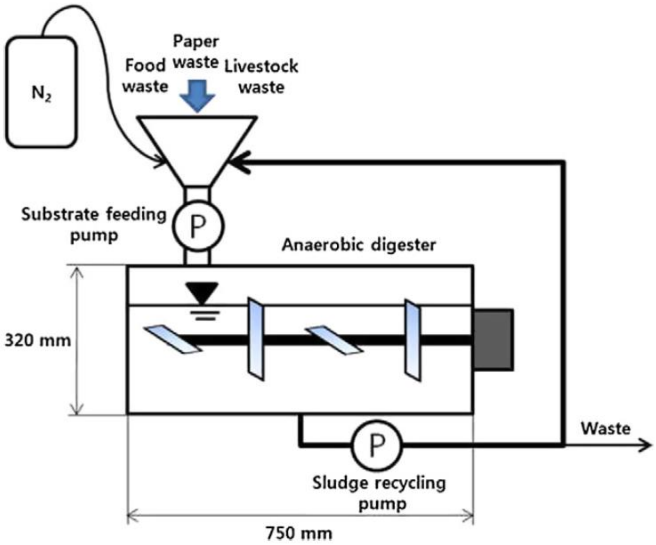

Fig. (1). Schematic of horizontal-type cylindrical reactor used for continuously anaerobic dry co-digestion of food waste with paper or livestock waste [25].

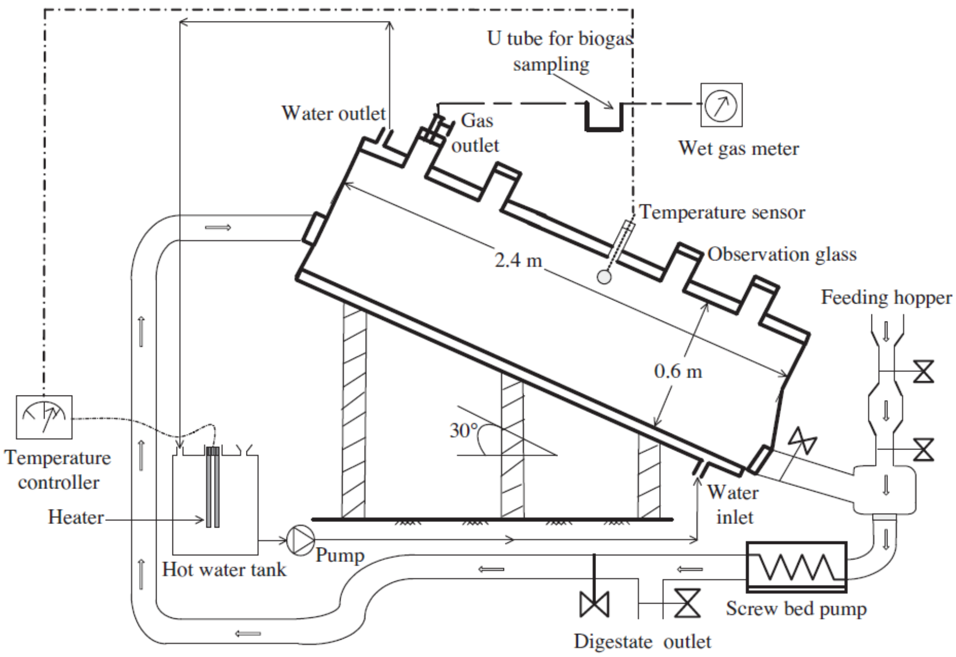

Fig. (2). Pilot-scale inclined thermophilic dry anaerobic digester (ITDAD) [32].

Enhancement Strategies

Among the above recent trials on dry AD processes, some of them obtained undesirable biogasification performance. The problems encountered in the failed dry AD systems can be mainly ascribed to the inhibition of accumulated ammonia or VFAs concentration resulting in unstable solubilization and imbalance between hydrolysis and methanogenesis. In addition, due to high solids content in the dry AD systems thus slower mass transfer effect in the substrate, some limitations like longer retention time and larger inoculation ratio may hinder its application in practice to some extent.

In general, three strategies are practically useful to improve the performance of dry AD to produce more bio-products: pretreatment of the feedstocks, acclimation of the microbes to dry AD condition, and co-digestion of carbon-rich (*i.e.* lignocellulosic materials) with nitrogen-rich feedstocks (*i.e.* animal manure or sewage sludge).

Pretreatment

Pretreatment sometimes is necessary, especially for lignocellulosic materials to produce biofuels. The pretreatment can be grouped into mechanical, physical, chemical and biological methods based on the nature of treatment. Single mechanical or physical methods sometimes are not so effective and thus always applied in combination with chemical or biological methods in practice.

Table **3** summarizes the main pretreatment methods recently used for dry AD in research works along with their treatment conditions and results. Some chemical methods like ammonia, lime and sodium hydroxide can achieve desirable pretreatment effects [4, 56-61], especially for lignocellulosic materials. The fermentation liquor, or biogas liquid can also be used to pretreat biomass for enhanced biogasification [62], possibly due to a combination of chemical (ammonia and acids contained) and biological effects. Some naturally microbial pretreatment methods like stack-pretreatment [63], and aerobic and facultative composting pretreatment [64, 65] have been demonstrated to be effective and beneficial for the subsequent dry AD of the pretreated biomass. Our recent study [66] shows that hydrothermal pretreatment is effective for rice straw based on subsequent hydrogen production, especially at 210℃ for holding 0 min. Moreover, Ariunbaatar *et al*. [12] compared the pretreatment methods in terms of their efficiency, energy balance, environmental sustainability as well as capital, operational and maintenance costs. Their results indicate that thermal pretreatment at low temperatures and two-stage anaerobic digestion methods could achieve higher efficiency in process performance compared to other pretreatment methods.

Acclimation or Adaptation

Dry AD is regarded as a mass transfer controlled process [67]. The controlling step is the relief of acid inhibition within the solids when carbon-rich feedstocks like lignocellulosic materials are used due to the fact that the produced VFAs might be much higher under dry AD conditions. On the other hand, when nitrogen-rich feedstocks like animal manure are treated by using dry AD, more attention should be given to ammonia inhibition. Many research works have been carried out on mitigation of ammonia inhibition, however, most of them were conducted under wet anaerobic conditions [10]. These works are not repeated in this review.

Table 3. Recent pretreatment methods used for lignocellulosic feedstocks

Method(s)	Feedstock	Pretreatment and biogasification conditions	Major results	Ref.
NaOH and Hydrothermal	Wheat straw	1) 4% NaOH (based on dry weight of wheat straw), 37℃, residence time of 120 h 2) Hydrothermal treatment at 200℃ for holding 10 min, 1.55 MPa 3) Biogasification: 37℃, C/N=25, TS=5%, HRT=60d, substrate/inocula=1	Improved biodegradability and biogas production were obtained: 1) Untreated straw: 188.4 ml/g-VS and 78.4 ml CH_4/g-VS. 2) NaOH pretreated straw produced 87.5% and 111.6% higher in biogas and methane yields: 353.2 ml/g-VS and 165.9 ml CH_4/g-VS. 3) Hydrothermal pretreated straw resulted in an increase of 9.2% and 20.0% in biogas and methane production: 205.7 ml/g-VS and 94.1 ml CH_4/g-VS.	[56]
Mechanical Chemical, and Enzymatic	Switchgrass	1) Pretreatment carried out in 0.5 L batch reactors, at 35℃ 2) Considering the effect of temperature, sonication, alkalinization and autoclaving on methane production	1) The substrate produced 112.4, 132.5 and 139.8ml/g-VS after 38 days of incubation after grinding, grinding with alkalinization, and grinding with alkalinization and autoclaving, respectively. 2) The methane production was increased by 29% and 42% when applying lignin (LiP) and manganese peroxidase (MnP) were applied, respectively. 3) The combination of alkali pre-treatment with MnP could further increase the methane production to be 297.7 ml g/VS. 4) Only using pectate lyase and polygalacturonase (without chemical pretreatment) could achieve 287.4 and 239.5 ml/ g-VS, respectively.	[58]
Thermal-chemical	Sugarcane press mud	1) Thermal-alkaline treatment condition: 100℃, $Ca(OH)_2$ 2) TS=9% 3) Methane potential assay: 37℃,	Improved COD solubilization and anaerobic biodegradability for methane yield were achieved: 1) Best pretreatment resulted in 72% increase in methane yield by adding 10 g $Ca(OH)_2$/100 g-TS for 1 h, yielding 272 ml CH_4/g-VS.	[61]

		inocula obtained from a large scale co-digestion plant	2) HAc was the major VFA formed during the pretreatment.	
NaOH	Fallen leaves	1) NaOH loading: 2%, 3.5%, and 5% (based on dried leaves) 2) Anaerobic fermentation: C/N=18-25, TS=20%, 37℃	1) The highest methane yield of 82 L/kg-VS was obtained at 3.5% NaOH and 4.1 of substrate-to-inoculum (S/I) ratio. 2) The greatest enhancement in methane production was obtained at S/I ratio of 6.2 and3.5% NaOH, about 24-fold higher than the control (no NaOH addition).	[4]
Ammonia	Wheat straw	1) Ammonia dosage (2%, 4%, and 6%, dry matter) and moisture contents (30%, 60%, and 80%, dry matter) with treatment duration of 7 days. 2) Batch AD assessment: 2L digester seeded with activated sludge, TS=50-80 g/L, 35℃	1) Wheat straw pretreated with 80% moisture content and 4% ammonia achieved the highest methane yield of 199.7 ml/g-VS, with shorter digestion time of 25 days at TS of 65 g/L compared to untreated straw. 2) The cellulose and hemicellulose contents were decomposed by 2%-20% and 26%-42%, respectively, while the lignin content was hardly removed.	[60]
Aerobic composting	Municipal solid waste	1) Aerobic pretreatment: 3 d, 45-68℃, TS=45-50% 2) Anaerobic digestion: batch hydrolysis reactors (HRT=12 d) and one 2.0 L continuous methane fermentor with liquid recirculation between hydrolysis and methanogenesis reactors.	1) Organic recovery ratio was 56% after aerobic composting. 2) Average TS, VS, VS/TS ratio and carbon/nitrogen ratio (C/N) were 50%, 36%, 0.72 and 26, respectively. 3) 38% TS reduction and 53% VS reduction in organic solids were achieved after AD treatment. 4) At the maximum loading (9.2kg-VS/(m^3·d)), biogas and methane yields were averagely 0.38 and 0.19 L/g-VS with average biogas production rate of 3.5 L/(L·d). 5) VFAs determined in the reactors were 15,000 mg/L, while little VFAs inhibition was observed in all the hydrolysis reactors due to liquid recirculation.	[64]

Composting (facultative)	Rice straw	1) Inoculum: water:rice straw=0.29:1.57:1 (w/w/w, moisture=65%) 2) Plastic drum was used for composting and covered with plastic film 3) Temperature 60-70℃, HRT 7 d	1) Lignin, cellulose and hemicelluloses contents were decreased by 13.6%, 64.5% and 7.5%, respectively after composting. 2) Dry AD of rice straw after composting achieved the highest biogas production of 353 ml/g-VS at initial TS=20%, 35℃ and C/N=30.	[65]
Stack-pretreatment	Corn straw	1) Stack: 1m in height. The temperature of middle part between 30 and 60 cm was 51-53℃ with bottom temperature > 70℃. 2) Anaerobic digestion: 5L, C/N=20, 25%TS and pH7.0 3) Inoculation with the effluent from wet digestion	1) The stack-pretreated corn straws (for 20 days) showed decreased cellulose, hemi-cellulose and lignin contents by 5.8%, 16.8% and 5.7% in the middle pile, respectively. 2) The biogasification efficiency was enhanced when the pretreated corn stover mixed with cow dung was used as feedstock.	[63]
Hydrothermal	Rice straw	1) Hydrothermal treatment at two different peak temperatures: 150℃ and 210℃ for holding 0-30 min, 20%TS 2) Batch hydrogen fermentation experiments: 250 ml glass bottles, seeded with anaerobic digested sludge, pH7.0, 35℃	1) No obvious degradation was detected in lignin content under all tested pretreatment conditions. 2) Hydrothermal treatment did open up the surface structure and had efficient solubilization effect on rice straw. 3) The maximum soluble carbohydrates was 80 mg per gram of VS achieved at 210℃ for holding 0 min, correspondingly yielding the highest hydrogen production (28 ml/g-VS), about 93-fold higher than the control.	[66]
Biogas liquid soaking	Maize straw	1) Pretreatment：9 days and 25℃	1) Dry matter digestibility increased to 73.76%. 2) The impact of the influential factors for pretreatment followed a	[62]

	with biogas liquid dosage of 50% (v/w) 2) Anaerobic fermentation by rumen microorganisms at 39℃ for 24 h	descending order: treatment duration > temperature > dosage of biogas liquid.

COD, chemical oxygen demand; HRT, hydraulic retention time; TS, total solids; VS, volatile solids.

Acclimation or adaptation is an economically feasible method to reduce the inhibition effect of toxic substances like VFAs or ammonia to the microorganisms, even under high solids condition. Results from Abouelenien *et al*. [24] show that spontaneous acclimation of methanogenic consortia to high levels of ammonia could occur, resulting in production of methane even under a high total solids (TS=25%) and a high level of ammonia (8 to 14 g-N per kg of chicken manure). A remarkable reduction in start-up time and stabilization period was observed by Fdéz.-Güelfo *et al*. [34] who observed a shortened period from 250 to 110 days by using the inoculum previously adapted not only to the operation conditions (thermophilic and dry) but also to the type of waste when applying the modified SEBAC system to treat OFMSW. As Martin *et al*. [68] pointed out, properly seeding is very important for quickly developing dry anaerobic methanogenesis process, making dry AD become an economic producer of renewable energy from various feedstocks.

Anaerobic Co-digestion

Anaerobic co-digestion, a simultaneous digestion of two or more substrates, is a feasible option to overcome the drawbacks of mono-digestion and to improve the treatment plant's economic feasibility [15]. A strong rise in co-digestion plants was noticed for MSW with other organic wastes in Europe in recent two years [6]. Stated, co-digestion is more important for the dry AD of C- or N-rich biomass.

Table **1** also lists some recent research works on dry anaerobic co-digestion. Among all the feedstocks, animal manure, sewage sludge, lignocellulosic waste and OFMSW are the most reported substrates used for co-digestion. Results from Yang *et al*. [69] show that co-digestion of *S. alterniflora* with potato can improve hemicellulose degradation, attributable to the increased concentration of VFAs which peaked about 11 g acetate equivalent (Ae)/L compared to 5 g Ae/L in the control (mono-digestion). The methane yield of *S. alterniflora* can be enhanced by 7 - 44% through anaerobic co-digestion with cow feces [70]. Anaerobic co-digestion of cattle slurry with food waste also shows that co-digestion can produce 70% higher electrical energy potential due to improved conversion efficiency and additional energy yield from cattle slurry [71]. Zeshan *et al*. [32] found that higher C/N ratio was necessary for stable dry AD of N-rich biowaste, which could buffer the inhibition effect caused by produced ammonia. Tyagi *et al*. [16] conducted batch experiments on thermophilic dry anaerobic co-digestion of OFMSW and sewage sludge for hydrogen production: The maximum hydrogen yield of 51 ml H_2/g-$VS_{reduced}$ was achieved at 20% TS and mixing ratio of OFMSW to mixed sludge of 5:1. Kim and Oh [25] tried the dry anaerobic co-digestion of food waste with paper waste and livestock waste. Their results show that under dry AD condition, co-digestion is more perspective: stable performance was obtained when HRT decreased to 40 d at TS of 40% and mixing ratio of 7/3 (weight basis), and the biogas production rate, CH_4 yield and VS reduction achieved under this condition were 5.0 $m^3/(m^3 \cdot d)$, 0.25 m^3 CH_4/g-COD_{added}, and 80%, respectively. When food waste was co-digested with animal manure, stable performance, *i.e.* 1.7 $m^3/(m^3 \cdot d)$ of biogas production rate, 0.26 m^3 CH_4/g-COD_{added} of CH_4 production yield and 72% of VS reduction could be achieved at a proper mixing ratio of 6/4.

Recent works also indicate that, besides MSW, dry AD can also be used to economically and effectively treat N-rich feedstocks like animal manure and sewage sludge for energy or other bio-products production when co-digestion processes are applied and operated under proper conditions.

As for other enhancement methods, like the combination of microbial electrolysis with iron-graphite electrode into dry AD process recently declared by Feng *et al*. [37] to be beneficial for the bioaugmentation of VFAs accumulation and CH_4 production when initial wasted sludge TS around 10 - 12%. Further investigations are still necessary for their feasibility of application in dry AD which has a much higher TS content (*i.e.* 20 - 40%).

CHALLENGES AND FUTURE DIRECTIONS

From 1980s on, dry AD starts to prevail over wet digestion, especially in Europe for the treatment of organic solid wastes. Several dry AD systems, including DRANCO, KOMPOGAS, VALORGA, BECON, and STRABAG have been developed and widely utilized in practice. As summarized by Kothari *et al*. [9], dry AD could achieve higher biogas production at less cost when TS = 20 - 50%, resulting in the same performance of VS reduction (40 - 75%) while much higher OLR of 12 - 15 kg VS/(m^3·d) in contrast to wet AD with lower OLR of < 5 kg VS/(m^3·d).

As seen from Table **2**, household organic waste is the major feedstock treated in the commercialized dry AD systems in which only single-stage anaerobic process has been adopted. Horizontal or vertical plug-flow type reactors are usually applied in continuous systems equipped with agitators, while batch systems are also attractive due to their easy handleability and low investment and operation costs. Besides the biogas produced and used for heating or electricity generation, the residue or digestate can be easily converted into high quality compost after simple post-treatment (dewatering or aerobic composting). As mentioned above, single-stage process and dry AD are estimated to account for 93% and 62% of the MSW treatment capacity installed in Europe in 2014, respectively [6]. Thus it's reasonably to predict that single-stage dry AD will continue to dominate the treatment and energy recovery from organic solid wastes if no breakthrough or no new merits of two-stage or multi-stage dry AD systems could be achieved to compete with single-stage dry AD systems. In addition, all of these commercialized dry AD plants are designed for methane production, and no report could be found on commercialized dry AD process for hydrogen or other bio-products production from organic solid wastes.

Although more than 180 dry AD plants have been installed up to present (Table **2**), this biotechnology is still facing some challenges which impede its fully application and management of the treatment process and energy recovery from various organic solid wastes. As pointed out by Li *et al*. [3], the techno-economic constrains of the large-scale dry AD plants are mainly associated with the following three aspects. (1)Due to its slower mass transfer, dry AD process usually has longer SRT compared to wet AD. Although some improvements have been documented in the newly developed dry AD reactors [25, 32], further improvement is still necessary for attaining the same short SRT as wet AD systems. (2) In order to make dry AD to be a competitive alternative to landfilling, the traditional low-cost technology to deal with solid wastes, further improvements on conversion efficiency and economics are in demand. And (3) further improvements are also necessary regarding the feedstocks pretreatment, stability control, and reactor design not only for MSW but also for crop residue and animal manure treatment.

From the viewpoint of sufficient pollution reduction and high energy production, some future directions are put forward below with expectation of further commercialization of dry AD.

Firstly, in order to maintain a continuous operation of dry AD process, feedstock collection and conservation is very important [72, 73]. How to cost-effectively collect, transport and store these organic solid wastes with little or less loss in organic ingredients is still challenging.

Secondly, when practical application is taken into consideration, how to control the stability of dry AD process is also of leading importance. One option is to develop efficient monitoring and characterization methods necessary for probing the changes of organics and microbial cells in the substrate during fermentation processes [74]. Online/inline reaction monitoring like pH, oxidation-reduction potential (ORP) of the digestate, biogas production and its composition might be a feasible way to inspect the on-going processes in the dry AD systems. When gas meter and infra red (IR) gas detector are applied, FT-IR technology may be helpful [32, 75]. Fast DNA extraction followed by PCR amplification and dHPLC quantification might be another feasible alternative, which has been used for the performance inspection on a 750 m^3 anaerobic digestion plant [76]. Moreover, the composition of gaseous phase can be measured by in-process instrumentation. A direct injection mass spectrometric technique, *i.e.* Proton Transfer Reaction Time-of-Flight Mass Spectrometry (PTRToF-MS) is regarded as a promising tool for rapid in situ bioprocess monitoring [77].

Thirdly, regarding to the energy consumption and energy balance in dry AD systems, the combination with other renewable energy like solar energy to develop more cost-effective dry AD reactors is also attractive and most promising [78]. According to the findings by Tyagi *et al*. [16] and Wang *et al*. [30], it is expected to be more promising for dry AD to achieve higher overall energy recovery by using two-stage or combined processes, such as using the first stage for H_2 or ethanol production and the second stage for methane production

Furthermore, being similar to wet anaerobic digestion, high ammonia concentration thus inhibition to anaerobic bacteria is still one of the major challenges for using dry AD to treat animal manure or sewage sludge. Effective control of ammonia in the substrate could achieve successful operation of dry AD [20]. Besides achieving the same biogasification performance, how to timely and effectively remove and recover ammonia from the fermentation systems is the key to success of dry AD in practice for the treatment of N-rich organic solid wastes (animal manure or sewage sludge) and nitrogen resource recovery.

The last, but most important, is that up to now the indices used to assess process stability like C/N ratio, VFAs and FAN concentrations, and VFAs/total alkalinity (TA) ratio are based on wet AD systems. Due to much difference between wet and dry AD reactors, the process assessment index system should be re-established so as to realize the effective control and management of dry AD systems.

CONCLUSION

Dry AD process is playing a leading role in the treatment of organic solid wastes due to its advantages like higher volumetric OLR and biogas production efficiency, less requirement of added water and less or no wastewater produced. Recent research shows that dry AD can be used to recover various bio-products including methane, hydrogen, VFAs, and ethanol from MSW, dewatered sewage sludge, animal manure and lignocellulosic materials. Up to now, only methane production by dry AD has been commercialized and successful. Single-stage and continuously operated dry AD will continue to dominate the practical application in the near future. Feedstock pretreatment, acclimation of microbes to dry AD condition, and co-digestion of C- and N-rich feedstocks are the three useful strategies to enhance the biogasification performance of dry AD systems, among which naturally microbial pretreatment and co-digestion could be more promising. Further improvements are still necessary for dry AD to achieve shorter SRT, cost-effectiveness, and easy process control, which can help to make dry AD systems to be more advantageous over other techniques for the treatment of organic solid wastes.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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