Chapter

Dry Anaerobic Digestion for Agricultural Waste Recycling

Shohei Riya, Lingyu Meng, Yuexi Wang, Chol Gyu Lee, Sheng Zhou, Koki Toyota and Masaaki Hosomi

Abstract

For sustainable agriculture, it is important to manage agricultural wastes, such as crop residues and livestock wastes. Anaerobic digestion has been gathering the attention to recycle these wastes into renewable energy (biogas) and fertilizer (soil amendment) (digestate). Dry anaerobic digestion is defined as digestion at higher than 20% of total solid (TS) content in the reactor, which is suitable for wastes with high TS content, such as agricultural wastes. In this chapter, we reviewed recent advances in biogas production and use of digestate as soil amendment from dry anaerobic digestion of agricultural wastes. It has been found that ammonia concentration, feed/inoculum (F/I) ratio, and TS content are important parameters for operation of dry anaerobic digestion. Several operation technologies have been in operation, while new operation strategies have been developed. Application of solid digestate into the soil is beneficial to increase soil properties; however it should be carefully operated because it has risks of nitrate leaching and soil pathogens.

Keywords: dry anaerobic digestion, biogas, crop residue, manure, soil amendment

1. Introduction

Providing energy and food with low environmental impact is considered as an urgent issue in order to meet demands of them for the growing global population. Alternative resources to replace fossil fuel for energy and chemical fertilizer production are required. Agricultural wastes, such as crop residues and livestock wastes, have been gathering attention as a source of renewable energy and nutrient [1]. Agricultural waste such as lignocellulosic biomass is available globally over 200 billion dry metric ton per year [2]. Livestock wastes such as manures are important nutrient source. Global estimates of nitrogen and phosphorus in the manures were 128 and 24 Tg for 2007, which are almost two times higher than those of fertilized chemical fertilizer [3].

Anaerobic digestion is a technology for treatment of organic wastes, which can biologically decompose carbohydrates, proteins, and lipids in the absence of oxygen and produce biogas (CH_4 and CO_2). In anaerobic digestion, nitrogen in protein and amino acids are mineralized and transformed into ammonium (NH_4^+). Total P and K are also not lost and retained in the digestate [4]. These nutrients are retained in the residue of anaerobic digestion, called digestate. Therefore, anaerobic digestion can produce both renewable energy and nutrients. In addition to organic waste treatment, anaerobic digestion can be utilized for effective biological pretreatment for anaerobic biorefinery [5]. In the anaerobic biorefinery concept, biogas is further transformed into alcohol or syngas, etc., and digestate is utilized for algae, organic acid, and alcohol biopolymer productions [6]. Digestate can be also applied to agricultural land as a fertilizer [7] for production of crops or forages since it contains nutrients as noted above. Recycling digestate as a fertilizer can reduce chemical fertilizer production, hence reducing fossil fuel consumption and CO_2 emission [8]. Harvested crop residues and collected manures from the livestock fed with the harvested forage can be used for substrate in anaerobic digestion. Thus, anaerobic digestion can be a key technology to recycle waste into value-added products and fertilizer.

Generally, anaerobic digestion is conducted in the form of liquid at low total solid (TS) content less than 15% [9], called wet anaerobic digestion. Wet anaerobic digestion is suitable for wastes with low TS contents (high-moisture contents) [10]. However, to maintain low TS content in the reactor, it requires a large amount of water if it treats wastes with high TS content, such as lignocellulosic biomass, resulting in increase in reactor volume as well as generation of a huge volume of wastewater to be treated [9]. In addition, digested slurry is subjected to solid–liquid separation process [11] after wet anaerobic digestion for further processing.

On the contrary to wet anaerobic digestion, operation at TS content of higher than 15% is classified as dry (solid-state) anaerobic digestion [9]. Dry anaerobic digestion has several advantages over wet anaerobic digestion such as less fresh water usage and favorable energy balance [12]. Agricultural waste such as lignocellulosic biomass has high TS content. For example, TS contents of the corn silage, grasses, and straw biomasses are 25–89% [13]. For livestock manure, depending on pretreatment (solid–liquid separation), TS contents of solid phase are 18–30% [13, 14]. Therefore, agricultural wastes are suitable in dry anaerobic digestion in terms of TS content. Total solid contents of the solid fraction after solid–liquid separation of wet digestate are 23–30% [15], which are comparable or slightly higher than TS content of the dry anaerobic digestate (TS content in the reactor) [16]. Therefore, it would be expected that dry anaerobic digestion would reduce post-digestate treatment such as solid–liquid separation and treatment of liquid fraction, which can reduce energy consumption and cost for plant construction and operation. Therefore, dry anaerobic digestion would have more advantages over wet anaerobic digestion for biorefinery of agricultural wastes.

Although dry anaerobic digestion has several benefits, still wet anaerobic digestion plants have more advantages in terms of energy balance and cost performance in practice [12], requiring more research on effective operation of dry anaerobic digestion. Operation parameters of dry anaerobic digestion should be carefully determined. In general, mass transfer in the dry digestion media is not adequate, and high organic loading would reduce degradation of substrate and biogas production [10]. In addition, treatment of waste with high nitrogen concentration, such as manure, would result in ammonia accumulation and failure [17].

Digestate from the anaerobic digester can be used as fertilizer as it contains nutrient for crop growth or further processed to produce value-added products as noted above. For digestate from wet anaerobic digestion, digestates are subjected to solid–liquid separation [18]. These liquid fraction and solid fraction can be used as fertilizer [18]. Numerous studies have been conducted to evaluate effect of digestate from the wet anaerobic digestion on crop production and environmental risks [15], while digestate from the dry anaerobic digestion has not been well studied.

In this chapter, we reviewed research progress in dry anaerobic digestion of agricultural waste. The key parameters and reactor types of dry anaerobic digestion were summarized. In terms of digestate recycling, we focused on the application of digestate in agricultural land. Especially, the effect of digestate from the wet and dry anaerobic digestion on soil nitrate leaching and root-knot nematodes was summarized.

2. Key parameters of dry anaerobic digestion

Anaerobic digestion is conducted by anaerobic microorganisms contributing to hydrolysis, acid production, and methane production. Therefore, operation parameters should be taken into account for their growth and inhibition. For example, manures containing high concentration of ammonia causes ammonia inhibition. In addition, higher TS content in the dry anaerobic digester causes slow mass transfer, resulting in slow decomposition of intermediate. The accumulation of the intermediate will result in inhibition of methane production. In this section, important parameters of dry anaerobic digestion were reviewed.

2.1 Ammonia concentration

Nitrogen is an essential nutrient for microorganisms conducting anaerobic digestion. However, excess amount of nitrogen causes inhibition. According to Rajagopal et al. [19], ammonia concentration between 50 and 200 mg N L^{-1} is beneficial for anaerobic digestion while higher than 1500 mg N L^{-1} inhibits digestion. In the solution, ammonium ion (NH_4^+) is equilibrated with free ammonia (NH_3). The equilibrium is governed by pH and temperature [20]. Therefore, higher pH and higher temperature increase NH_3 concentration. Free ammonia can diffuse into the cell through the cell membrane and inhibits cell function by disrupting the proton and potassium balance [21]. Therefore, thermophilic (55°C) condition is more sensitive to ammonia inhibition than mesophilic (37°C) condition.

In the dry anaerobic digestion, ammonia inhibition was reported in digestion of high nitrogen-containing biomass or digestion of low nitrogen-containing biomass with inoculum with high nitrogen concentration. Under thermophilic conditions, dry anaerobic digestion of corn stover highly inoculated with wet anaerobic digestion effluent showed smaller amount of biogas production than those with less inoculated one [22]. This was due to high concentration of ammonia in the inoculum. In semi-solid (10% of TS) digestion of chicken manure, 12 and 16 g N L^{-1} of ammonia were accumulated in mesophilic and thermophilic conditions, respectively, and the mesophilic condition showed higher methane production than that of thermophilic one [23]. Zhou et al. also observed low methane yield of thermophilic anaerobic digestion of pig manure, in which NH_4^+ concentration exceeded 4000 mg N kg^{-1} [17].

In order to overcome ammonia inhibition, several approaches were suggested such as ammonia striping, chemical precipitation, adjusting carbon/nitrogen (C/N) ratio, etc. Ammonia stripping was applied for dry anaerobic digestion of chicken manure. Ammonia in the chicken manure was stripped at high pH with N_2 flow after ammonia production by anaerobic fermentation [24]. Ammonia-stripped chicken manure showed 2305 mL kg^{-1} TS of cumulative methane production, which is much higher than the manure without stripping (313 mL kg^{-1} TS) [24]. In anaerobic digestion, C/N ratio of 15–30 is thought to be preferable [25]. A simple way to avoid ammonia inhibition is co-digestion with biomass with low nitrogen content such as crop residue. Co-digestion can dilute ammonia concentration in the reactor and reduce ammonia inhibition. For example, Abouelenien et al. found 1.5–93% increase in methane production in thermophilic co-digestion of chicken manure (C/N ratio of 6) with agricultural waste (coconut, coffee grounds, and cassava; C/N ratio of 17) compared with mono-digestion of chicken manure. Zhou et al. mixed pig manure with rice straw to obtain mixtures with C/N ratio of 10, 20, and 30 and conducted dry thermophilic digestion. The methane yields of C/N ratio of 20 and 30 were 244 and 258 mL g^{-1} VS, while C/N ratio of 10 showed lower and unstable methane production [17].

2.2 F/I ratio

In batch dry anaerobic digestion, the ratio of feed (substrate) and inoculum (F/I or S/I ratio), which is an index of organic loading to microorganisms, is an important parameter for efficient digestion. Operation with higher F/I ratio can treat larger amount of substrate in one batch. In the studies of dry anaerobic digestion, F/I ratios of 0.5–10 were applied or evaluated [22, 26–28]. Generally, increase in F/I ratio results in slower startup and lower methane yield than those of lower F/I ratio. For example, in mesophilic dry anaerobic digestion of corn stover, F/I ratio of 2.43 showed the highest methane yield (321 L kg^{-1}), followed by F/I ratios of 3.44, 4.58, and 7.41 [22]. Co-digestion of rape straw and dairy manure also showed higher methane yield (209 L kg^{-1}) in low F/I ratio (2:3 of feed/inoculum) than those in higher F/I ratio [29].

The reason why dry digestion at higher F/I ratio failed is acidification of the reactors by accumulation of volatile organic acids (VFAs). Li et al. observed that the final pH in failed reactors at F/I ratio of 4.58 and 7.41 were 5.43 and 5.11, respectively, in digestion of corn stover [22]. According to the VFA concentration and pH changes during digestion, overaccumulation of VFAs (up to 25 g L^{-1}) and drop of pH (less than 6) caused inhibition of methane production at high F/I ratio (3 and 4) [29]. Most methanogens are active in pH of 6.6–7.6 with an optimum pH of ca. 7. Therefore, acidification by accumulation of VFAs causes reduction of methane production activity. In addition to its influence to methanogens, high F/I ratio affects hydrolysis. Cui et al. observed cellulose and hemicellulose degradation rates were about 40% in dry anaerobic digestion of spent wheat straw at F/I ratio of 2 and 4, while it was less than 10% at F/I ratio of 6 [30]. Similar results were also observed in dry anaerobic digestion of solid waste residues of palm oil mill industry [31]. At pH of 6, the performance of hydrolysis and VFAs production was lower than at higher pH in fermentation of lignocellulosic waste [32]. Therefore, lowering pH may affect all the processes of anaerobic digestion (hydrolysis, VFA production, and methane production).

2.3 Total solid content

High TS content can reduce reactor volume and capital cost [9]. However, in dry anaerobic digestion, higher TS content reduces methane production. Xu et al. reported that maximum methane production rates were proportionally increased with TS content between 0 and 20% while gradually decreased from 20% TS to 30% TS content in mesophilic digestion of corn stover [33]. For mesophilic dry digestion of empty fruit bunch and oil palm trunk, methane yields at 16 and 25% TS contents were 250–350 mL g^{-1} VS. At 35% TS content, however methane yields were less than 100 mL g^{-1} VS with some exception [31]. In semi-batch dry thermophilic co-digestion of pig manure and rice straw, biogas yields were around 600 mL g^{-1} VS, and no VFAs accumulation was observed between 18% and 27% of TS content in the reactor [16]. However, biogas production was decreased concomitantly with VFAs accumulation when TS content in the reactor exceeded 28% [16]. Therefore, TS content should be carefully chosen and managed.

According to Le Hyaric et al., increasing TS content resulted in linear decrease in methane production from acetate, propionate, and cellulose [34]. They pointed out that acetate removal is a rate-limiting step in dry anaerobic digestion since H_2 produced from cellulose degradation was rapidly consumed and showed higher methane production than degradation of acetate [34]. However, there have been less information on rate-limiting step at high TS content. More study is required.

It has been thought that slow solute transport would cause reduction of biogas production at high TS content. In the dry anaerobic digestion, molecular diffusion is thought to control solute transport within the digestion medium because mixing is limited [35]. Solute flux by molecular diffusion is proportional to solute concentration gradient. And its proportional constant, called diffusion coefficient, characterizes the extent of the solute transport by molecular diffusion. Less information are available on the measurement of diffusion coefficient in the dry anaerobic digestion media. Several studies measured diffusion coefficient at high TS content. According to Bollon et al., diffusion coefficient of the solutes in the water is in the order of 10^{-9} m^2 s^{-1} while in the order of 10–11 m^2 s^{-1} at 8–25% of TS in digestate of the biowaste [35]. Similar results were also obtained by Zhang et al., who measured dewatered and digested sludge at 6–15% of TS content. Abbassi-Guendouz et al. demonstrated that limiting the overall mass transfer resulted in lower cumulative methane production [36].

3. Operating strategies of dry anaerobic digestion process

In dry anaerobic digestion process, major drawbacks are the heterogeneous distribution of substrate and microorganisms as well as low mass transfer under high solid content (> 20%). Inoculation efficiency of substrate is reduced by these factors, which results in unstable operation and low methane yield [37, 38]. Thus, keeping the inoculating efficiency is a main challenge for the operation of dry anaerobic digestion process.

Over the past 30 years, dry anaerobic digestion process has been developed and marketed by different companies in Europe. Commercial dry anaerobic digestion processes such as Valorga, Dranco, Kompogas, Bekon, and Bioferm are the most prevalent processes for treating municipal solid waste (MSW), biowaste, livestock waste, as well as green waste (**Table 1**) [10, 39]. According to several reviews [39–41],

Technology			Waste	Temperature (ºC)	TS (%)	SRT*/ Digestion period (days)	Biogas yield (m³/t**)	Capacity (1000 tons/year)	Plants***
Full scale	Continuous	Valorga	MSW****	35, 55	25–35	16–35	80–160	10–498	27
		Dranco	MSW	55	20–50	13–30	103–147	3–320	32
		Kompogas	MSW, green waste	55	23–28	15–20	110–130	15–274	25
	Batch	Bekon	Biowaste, agricultural waste	35, 55	Na	28–35	130	4.5–60	60
		Bioferm	Food waste, green waste, agricultural waste	35	25	28	Na	8	9
							Methane yield	Scale (L)	
New case studies	Continuous	Kim and Oh [49]	Food waste, livestock waste	35	30–50	30–100	250 L/g COD	60	Na
		Zeshan et al. [48]	MSW	35–55	18	13–153	121–327 L/kg VS	690	
	Batch process	Meng et al. [51]	Rice straw, pig manure	55	20	40	191 L/kg VS	0.5	

*: Sludge retention time
**: Wet weight base
***: Accessed at 30 December 30, 2019
****: Municipal solid waste
Na: No data

Table 1.
Performance and parameters of commercial and new case studies of dry anaerobic digestion process. source: Data from the company websites as of December 2019 and adapted from Nichols [45], Lei et al. [40] and Andre et al. [39].

current strategies for improving the inoculating efficiency in dry anaerobic digestion process are mainly based on two considerations: (1) to homogenize the distribution of substrate and microorganisms by mechanical (biogas) mixing and (2) to improve the mass transfer in digester by the recirculation of liquid digestate. Also, some new efforts for improving the performance of dry anaerobic digestion process also have been conducted.

3.1 Homogenization

To improve homogenization, several different types of continuous dry anaerobic digestion processes such as Valorga (France), Kompogas (Switzerland), and Dranco (Belgium) have been proposed. In continuous digesters, wastes (substrate) are added to the digester at regular intervals, and equal amounts of finished products (digestate) are removed. For example, Valorga process sets a central baffle in the vertical steel tank, and the baffle extends two thirds of the way through the center of the tank. Wastes are forced to flow around the baffle from the inlet to reach the outlet port on the opposite side, creating a plug flow in the reactor. Pressured biogas is provided at the base of the tank at intervals, which promotes the moving up of wastes to the opposite side of the tank and the contact between wastes and mature digestate (**Figure 1a**). This process was operated under the following conditions: total solid content of 25–35% and sludge retention time (SRT) of 15–20 days. Approximately 80–160 $m^3\ t^{-1}$ of biogas can be recovered [42, 43]. Solid digestate generated from the process can be used as soil amendment after being dewatered and stored under aerobic conditions [40].

Similar to Valorga process, vertical tank is also used in Dranco process. However, different to Valorga process, Dranco process performs the mixing of wastes and finished digestates by a special pump (mix and introduce the mixture of wastes and finished digestates to the pipeline) before introducing the mixture into the inlet located at the top of the tank. Thereafter, introduced mixture moves from the top to the bottom (outlet) by gravity without any internal mixing mechanism during digestion (**Figure 1b**). Total solid content in Dranco process usually ranges from 20 to 50%, while the SRT ranges from 13 days to 30 days. Approximately 103–147 $m^3\ t^{-1}$ of biogas can be recovered [41, 44].

Different to Valorga and Dranco processes, Kompogas digester is a horizontal steel tank with slowly rotating axial mixers that assist in conveying the material from the inlet to the outlet, keep heavy solids in suspension, and degas the thick digestate. Finished digestates are recycled to inoculate the fresh wastes (**Figure 1c**). TS in Kompogas process usually ranges from 23 to 28%, and processed water may be added to reduce the solid content, while the SRT ranges from 15 days to 20 days. Approximately 110–130 $m^3\ t^{-1}$ of biogas can be recovered [41, 45].

3.2 Promotion of mass transfer

In order to improve the mass transfer in the digester, the batch dry anaerobic digestion process with percolation system has been proposed. This system recycles leachate into the digester and enables the colonization of bacteria throughout the digester by promoting the transport of microbes and dissolved substrate. Premix of wastes and finished digestate is usually performed to inoculate the wastes. Currently, Bekon (Germany) has the main market share in batch dry anaerobic digestion process. As shown in the diagram of Bekon process (**Figure 1d**) [46], the premixed wastes and finished digestate are set in the "garage-type" digester, and leachate is collected from the bottom of the digester (digester at a 15 degree angle

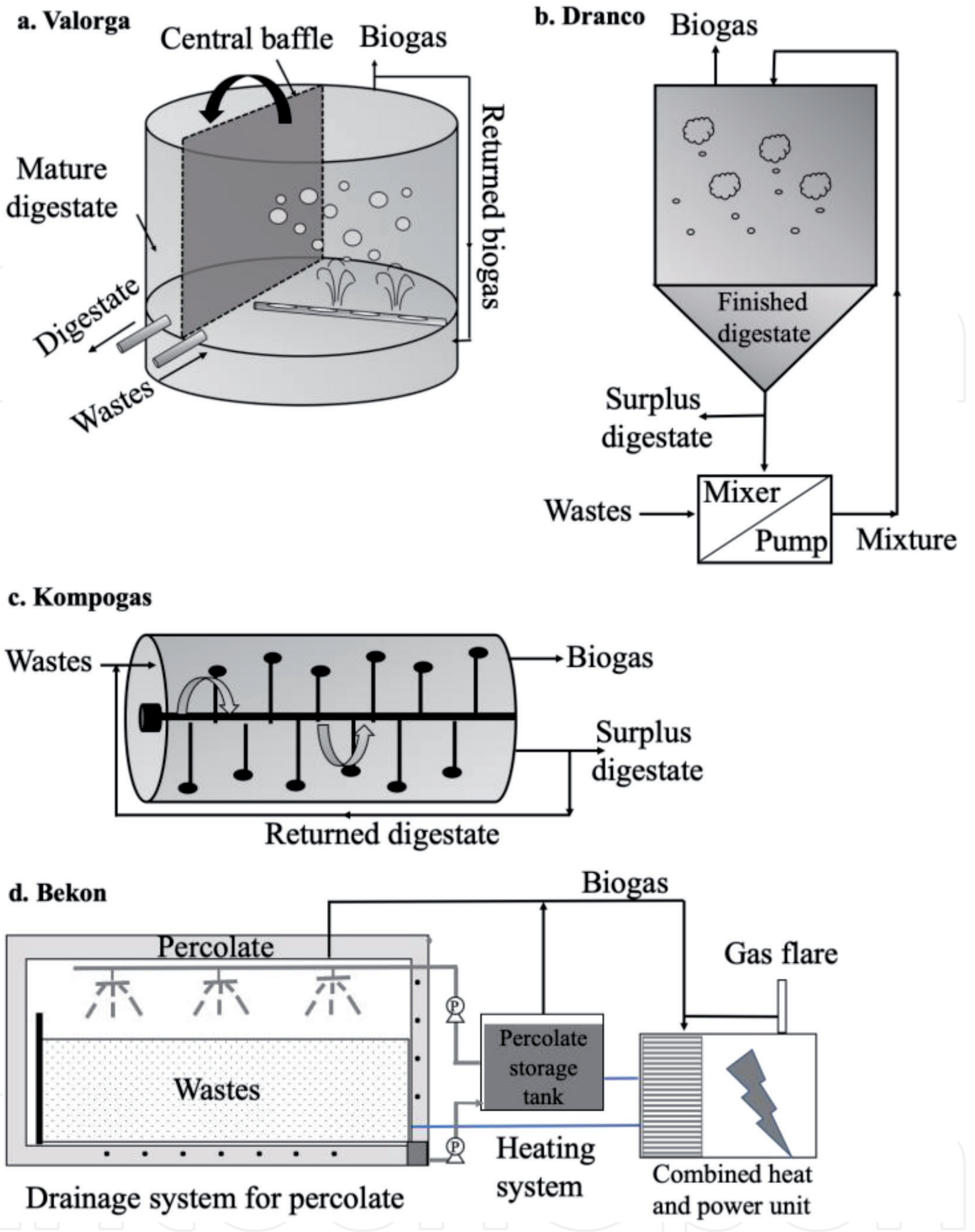


Figure 1.
Dry anaerobic digester designs.

for the leachate collection) and stored at the percolate digester for recycling. Mass transfer in the digester can be promoted by this cycling. Biogas collected from digester and percolate digester is converted into electricity in combined heat and power units (CHP) directly. Digestion period of Bekon process ranges from 28 days to 35 days, and approximately 130 m^3/t of biogas can be recovered [40, 47].

Almost similar to Bekon process, Bioferm (Germany) process also performs the treatment using "garage-type" digester. However, only mesophilic digestion is conducted in Bioferm process, while both mesophilic and thermophilic digestions are conducted in Bekon process. Bioferm process generally operates with a TS content of 25% and a digestion period of 28 days [39].

3.3 New efforts for operating dry anaerobic digestion process

More recently, several new operations of dry anaerobic digestion digesters 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.

Zeshan et al. developed a new type of continuous digester, which is called inclined thermophilic dry anaerobic digestion (ITDAD) system [48]. Their pilot-scale experiments indicated that the maximum specific methane yield was 327 L kg^{-1} VS added at total ammonia nitrogen (TAN) of 1895 mg L^{-1} and TS content of 18% (**Table 1**). Kim and Oh proposed a horizontal-type cylindrical continuous digester for the co-digestion of high solids of food waste with paper waste or animal manure [49]. The reactor operates with a TS content of the input wastes ranging from 30 to 50%, and SRT ranges from 30 days to 100 days. 250 L g^{-1} COD_{added} of methane can be recovered when the reactor was applied to co-digestion of food waste with paper waste at SRT of 40 days and 40% of TS content under mesophilic conditions (**Table 1**). The performance they obtained was comparable to the conventional wet digestion and thermophilic dry anaerobic digestion processes.

In terms of liquid recirculation during batch dry anaerobic digestion, most previous studies have focused on optimization of the leachate-to-substrate ratio, the recirculated leachate volume, and recirculation frequency [38, 50]. Meng et al. tested two liquid circulation modes (percolation and immersion) during batch thermophilic dry anaerobic digestion of rice straw using pig urine for liquid circulation [51]. In the percolation mode, leachate was poured on the rice straw-filled mesh bag, while liquid content was passed through the bag. For immersion, the rice straw-filled mesh bag was immersed in the leachate for the designated contact time. Leachate recirculation by percolation might cause nonuniform leachate flow because of the heterogeneous structure of the medium [52], while it is expected that most of the substrate in the bag could be in contact with the leachate by immersion. The methane yield of the immersion mixture of rice straw and solid digestate into leachate was higher than that of percolation of leachate. Furthermore, the methane yield increased from 1 to 24 h of the immersion period, while it decreased after longer than 24 h of immersion. Therefore, pig urine can be used as liquid recirculation medium under certain conditions. However, large-scale validation is needed.

Moreover, the startup and control of dry anaerobic digestion tends to be more difficult than liquid anaerobic digestion, due to the low mass transfer in dry anaerobic digestion [34]. In commercial dry digester, approximately 50–70% of the finished digestate need to be reused as inoculum, which reduces the efficiency of waste treatment [53]. Recently, several studies have pointed that the finished material (effluent) from liquid anaerobic digesters is the best inoculum for dry anaerobic digestion [53, 54]. This is because liquid digestate can provide supplement nitrogen, water, trace elements, and alkalinity to the system [55, 56]. Xu et al. [57] compared the performance of the dry anaerobic digestion yard trimming of using solid digestate and dewatered effluent from liquid anaerobic digester as inoculum. They found that comparable methane yield and volumetric methane productivities are generated at each F/I ratio (0.2–2, based on TS weight) when conducting the digestion using these two kinds of inoculum, while startup time is reduced using dewatered effluent as inoculum. However, the studies are limited in laboratory scale; liquid anaerobic effluent has not been applied in commercial-scale dry anaerobic digestion process, due to the difficult transportation of liquid digestate (effluent) to dry anaerobic digestion plant. A pilot-scale integrated anaerobic digestion process by combining liquid anaerobic digestion and dry anaerobic digestion has been reported in Li et al. [58]. Liquid anaerobic digestion and dry anaerobic digestion are constructed side by side, and liquid digestate is used as inoculum for dry anaerobic digestion. However, larger-scale studies should be considered in the future studies for doing the better choice.

4. Digestate from dry digestion for soil amendment

4.1 Nitrate leaching risk after biogas digestate amendment

Anaerobic digestion is the degradation of organic substrates to biogas and produces a by-product "anaerobic digestate" which contains significant amounts of mineral nitrogen (N), which is available for plants [59]. Biogas digestate typically has a high concentration of ammonium (NH_4^+) and relatively little carbon (C), with NH_4^+-N accounting for 35–81% of total N and a C/N ratio of 2.0–24.8 [15, 18]. Moreover, it contains other macro- and micronutrients that are necessary for plant growth [7, 60].

The merits and demerits in the application of biogas digestate have been addressed in numerous papers. For example, the benefits are to improve the soil properties by reducing the bulk density, to increase the saturated hydraulic conductivity and the moisture retention capacity [61, 62], to sustain soil organic matter concentrations [63, 64], to enhance biological activities [59, 65, 66], and to suppress pathogenic organisms [15, 67]. In contrast, the demerits are to enhance nitrate leaching risk and to bring chemical and biological contaminations, such as heavy metals, organic pollutants [15, 68–70], *Salmonella*, and *Escherichia coli*, which are the most prevalent pathogenic microorganisms found in manures [71, 72].

Once biogas digestate is applied to a field, the NH_4^+-N is subjected to different processes: volatilization, absorption by clay particles, take-up by plants, immobilization into soil organic matter, and/or nitrification [73]. In general, NH_4^+-N in biogas digestate is readily nitrified to nitrate (NO_3^-) in soil [74–76]. Since few NO_3^- can be absorbed by soil particles, most of excess NO_3^- moves downward with drainage water and is eventually leached from the soil profile [77]. Many studies have reported the application of biogas digestate enhances NO_3^- leaching risk in the soil [76, 78–80]. In particular, the nitrate leaching potential is much higher in soil with neutral pH soil than in soil with lower pH [81, 82].

Stumborg [83] reported that dynamics of inorganic N, especially NO_3^-, is directly influenced by the soil type, climate, frequency of application, and property of the digestate. Rigby and Smith [84] conducted a laboratory experiment to investigate the effect of digestate deriving from different waste types (industrial, agricultural, and municipal solid waste or sewage sludge) on the N dynamics in three types of soil (sandy loam, sandy silt loam, and silty clay) and found that NO_3^- concentration was higher in sandy loam and NO_3^- did not accumulate in silty clay soil due to denitrification. Therefore, it is necessary to consider nitrate leaching risk in applying biogas digestate to an agricultural field from different aspects, such as the properties of digestate, soil type, and moisture content.

4.2 Biogas digestate mixed with crop residue to mitigate nitrate leaching risk

Several management strategies have been proposed to mitigate nitrate leaching: (i) limiting N application rates, (ii) synchronizing N supply to plant demand, (iii) adopting cover crop techniques, (iv) using nitrification inhibitors, and (v) applying a C source such as wheat or rice straw [85]. Incorporating digestate with straw residue from harvested crops is a promising practice to retain NO_3^- in the soil. Crop residue with a low C/N ratio degrades fast [86, 87], which increases the soil microbial biomass [88] and stimulates net N mineralization [87, 89]. In contrast, crop residue with a high C/N ratio stimulates net N immobilization, leading to a lower risk of NO_3^- leaching [90]. Previous studies have indicated that applying organic manure [91] or mineral N fertilizer [92] with straw (high C/N ratio) into cultivated soils reduced the accumulation of NO_3^- in the soil, since soil microbes use labile C contained in straw as an energy and carbon source with rapid microbial N immobilization [93, 94], thus decreasing NO_3^- leaching [95].

Wang [82] showed that NO_3^- concentration was the lowest in the treatment of biogas digestate mixed with a high amount of rice straw to adjust the C/N ratio from 12 to 30 (Mix2). The NO_3^- concentration in soil was much lower in Mix2 for a 90-day incubation period than in the other treatments, such as only biogas digestate and chemical fertilizer, indicating that most of the N added to Mix2 was microbially immobilized. Other studies also indicated that application of straw induced net N immobilization during the initial stages and released N at a later stage and the timing is largely dependent on climatic and soil factors including soil fertility [96–98]. It has been reported that application of crop residues reduces N losses and causes greater N retention in soil [99]. Yang [94] showed from a 5-year field experiment that straw application reduced soil NO_3^- leaching losses by 13% compared with the control treatment.

It is a matter of concern when N transformation process changes from immobilization to mineralization. In Kikugawa soil (pH = 7.0), the markedly low NO_3^- in Mix2 started to increase from day 35, indicating the net re-mineralization of the once immobilized N and soil organic N from day 35. In contrast, in Fuchu soil (pH = 5.7), NO_3^- started to increase only after day 60, indicating that microbial immobilization consistently dominated the nitrogen cycling process for the first 60 days. The period of N retention and N supply processes differ among soils [100]. Zhao [101] reported that N retention was much longer in a soil with lower pH (5.3) than in a soil with neutral pH (7.6). Soil fertility may also be involved in the change from N immobilization to N mineralization, since Pan [95] reported that N mineralization starts earlier in a fertile soil after the occurrence of N immobilization. Kikugawa soil (total C: 73.2 g kg^{-1} soil) showed higher fertility than Fuchu soil (total C: 35 g C kg^{-1} soil), and thus the earlier change from N immobilization to N mineralization occurred in fertile Kikugawa soil.

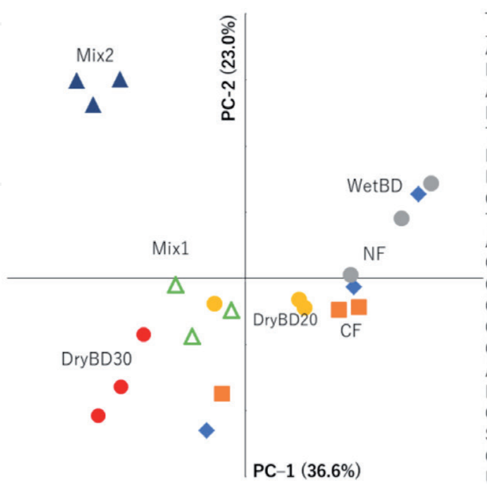
4.3 Effect of biogas digestate application on root-knot nematode

Root-knot nematodes (*Meloidogyne* spp.) are the most economically damaging group of plant-parasitic nematodes (PPNs) worldwide [102–104]. The genus *Meloidogyne* is composed of approximately 100 species and parasitizes thousands of plant species [105, 106]. This parasitism results in poor host plant growth and presents a serious threat to the production of many important horticultural and field crops [107–109]. As countermeasures, several means with nematode-suppressive properties have been reported, such as applications of compost with a low C/N ratio (< 20) [110, 111], volatile fatty acids [112], chitin [113], and plant-specific toxins [114]. A few studies also showed that application of biogas digestate to soil reduced the root gall formation of root-knot nematodes of tomato [115] and the damage to sugar beet by *Heterodera schachtii* [116].

A recent study showed that populations of *M. incognita* did not decrease in soil added with dry biogas digestate (C/N ratio of 20) treatment, compared with those in chemical fertilizer treatment [82]. Several studies have already reported that not all types of organic amendments are beneficial in the suppression of root-knot nematodes [117, 118]. For instance, Bulluck [117] also observed that

M. incognita populations were not affected by amendments of swine manure and composts. There are several factors which determine the effect of organic fertilizer on plant-parasitic nematodes, and the most commonly reported one is C/N ratio [119]. Organic amendment with a C/N ratio in the range of 15–20 was considered most effective [114]. In a study by Agu [120], plants of African yam bean treated with poultry and farmyard manures (C/N ratio of 4 to 12) showed a lower degree of disease caused by root-knot nematodes than those with other organic manures with C/N ratios higher than 30. In the study by Wang [82], the populations of *M. incognita* drastically decreased in Mix 2 treatment, in which biogas digestate was co-added with rice straw to increase its C/N ratio from 12 to 30.

Organic amendment may have different effects on different soil microbial groups, and nematodes could be reduced by such a modified microbial group [119, 121]. The prokaryotic community structure of the treatments reported by Wang [82] was evaluated, and the results showed that Mix2 treatment, in which low NO_3^- risk and high nematode suppression were confirmed, was separated from the other treatments, indicating that a specific microbial community was developed in the treatment (**Figure 2**). Several papers have already reported that the application of biogas digestate affected the community structure of bacteria and fungi [122–124]. In general, organic amendment stimulates a broad range of (micro) organisms involved in the soil food web, many of which are potential predators, such as diplogasterid [125] and dorylaimid [126], or invertebrate antagonists, such as enchytraeids and earthworms [127]. Moreover, nematode suppression might result from increased incidences and levels of nematode-antagonistic fungi following amendment application. According to Wang [128, 129], the application of sunn hemp crop residues to soil decreased the population levels of the plant-parasitic nematode *Rotylenchulus reniformis* and increased levels of nematode-trapping fungi, such as *Arthrobotrys oligospora* [130] and *Ematoctonus leiosporus* [131]. The mode of action in biogas digestate leading to nematode suppression and stimulation of microorganisms is complex and dependent on the nature of the original wastes. Therefore, long-term use of biogas digestate to build suppressive elements of the soil food web remains an elusive goal.



	NF	CF	WetBD	DryBD20	DryBD30	Mix1	Mix2
Alphaproteobacteria	10.1	10.7	10.3	10.5	10.5	11.1	11.1
Bacilli	8.2	8.4	8.7	9.3	12.6	8.3	11.5
Actinobacteria	6.1	6.7	6.7	6.8	6.7	6.9	9.4
Betaproteobacteria	7.4	7.2	6.5	6.5	6.4	6.8	5.9
Thermoleophilia	6.8	7.0	6.3	6.3	6.8	6.6	6.0
Deltaproteobacteria	5.4	5.1	5.2	5.0	5.0	5.2	6.0
Planctomycetia	5.3	4.8	5.3	4.9	4.3	4.7	4.8
Gammaproteobacteria	4.0	4.3	4.2	4.2	3.9	4.3	4.6
Thaumarchaeota	3.9	4.5	4.4	4.9	3.9	4.1	3.7
Acidobacteria-6	2.9	3.0	2.9	2.8	2.7	3.0	2.7
Chloroflexi;c__TK10	2.7	2.7	1.3	2.7	3.2	2.8	2.5
Chloroflexi;c__Ellin6529	2.7	2.6	2.6	2.6	2.5	2.6	1.8
Chloroflexi;c__Gitt-GS-136	2.2	2.5	2.2	2.3	2.5	2.3	1.5
Chloroflexi;c__Anaerolineae	2.6	2.1	2.5	2.1	1.8	2.0	1.7
Gemmatimonadetes	2.3	2.3	1.6	2.0	2.2	2.3	1.9
Acidimicrobiia	2.0	1.9	2.1	2.1	2.0	2.1	1.9
Phycisphaerae	2.3	2.0	2.3	1.8	1.4	1.6	1.4
Gemmatimonadetes	1.6	1.8	1.7	1.7	1.6	1.6	1.4
Saprospirae	1.7	1.7	1.8	1.6	1.1	1.4	1.4
Others	17.9	16.8	18.7	17.8	17.1	18.3	16.8
Unassigned	2.1	2.0	2.5	2.3	2.0	2.2	2.0

Figure 2.
A Uni-Frac weighted PCA analysis of prokaryotic communities of soils with different amendments and incubated for 90 days. NF: no fertilizer, CF: chemical fertilizers, DryBD20: dry biogas digestate with an C/N ratio of 12, DryBD30: dry biogas digestate with an C/N ratio of 16, Mix1: DryBD20 mixed with a low amount of rice straw to adjust its C/N ratio to 16, Mix2: DryBD20 with a high amount of rice straw to adjust its C/N ratio to 30.

5. Conclusion

Dry anaerobic digestion is appropriate for treatment of agricultural waste with high TS content. Optimization of C/N ratio, F/I ratio (or organic loading rate), and TS content is key to avoid failure of digestion. Several batch and continuous dry digestion technologies have been already applied in practice, while new techniques have been also proposed. Solid digestate is beneficial to supply nutrient into the soil and improve soil properties. On the other hand, nitrate leaching is one of the concerns of the digestate application. Digestate C/N ratio adjustment by mixing with crop residue can mitigate nitrate leaching. In addition, it can also mitigate root-knot nematode. More study is needed to optimize dry anaerobic digestion and digestate use for sustainable agricultural waste management.

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Conflict of interest

The authors declare no conflict of interest.

Author details

Shohei Riya[1*], Lingyu Meng[1], Yuexi Wang[2], Chol Gyu Lee[2], Sheng Zhou[3], Koki Toyota[2] and Masaaki Hosomi[1]

1 Graduate School of Engineering, Tokyo University of Agriculture and Technology, Tokyo, Japan

2 Graduate School of Bio-Applications and Systems Engineering, Tokyo University of Agriculture and Technology, Tokyo, Japan

3 Eco-Environmental Protection Research Institute, Shanghai Academy of Agricultural Sciences, Shanghai, China

*Address all correspondence to: sriya@cc.tuat.ac.jp

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