

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

4,800

Open access books available

122,000

International authors and editors

135M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.

For more information visit www.intechopen.com



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 CO₂ 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 (NH₄⁺) is equilibrated with free ammonia (NH₃). The equilibrium is governed by pH and temperature [20]. Therefore, higher pH and higher temperature increase NH₃ 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 NH₄⁺ concentration exceeded 4000 mg N kg⁻¹ [17].

In order to overcome ammonia inhibition, several approaches were suggested such as ammonia stripping, 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 N₂ 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 $250\text{--}350 \text{ mL g}^{-1} \text{ VS}$. At 35% TS content, however methane yields were less than $100 \text{ mL g}^{-1} \text{ VS}$ with some exception [31]. In semi-batch dry thermophilic co-digestion of pig manure and rice straw, biogas yields were around $600 \text{ mL g}^{-1} \text{ VS}$, 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 $10^{-9} \text{ m}^2 \text{ s}^{-1}$ while in the order of $10\text{--}11 \text{ m}^2 \text{ s}^{-1}$ 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 (°C)	TS (%)	SRT*/ Digestion period (days)	Biogas yield (m ³ /t**)	Capacity (1000 tons/year)	Plants***	
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
Full scale	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
New case studies	Kim and Oh [49]	Food waste, livestock waste	35	30–50	30–100	250 L/g COD	60	
	Zeshan et al. [48]	MSW	35–55	18	13–153	121–327 L/kg VS	690	Na
	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 $80\text{--}160\text{ m}^3\text{ t}^{-1}$ 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 $103\text{--}147\text{ m}^3\text{ t}^{-1}$ 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 $110\text{--}130\text{ m}^3\text{ t}^{-1}$ 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

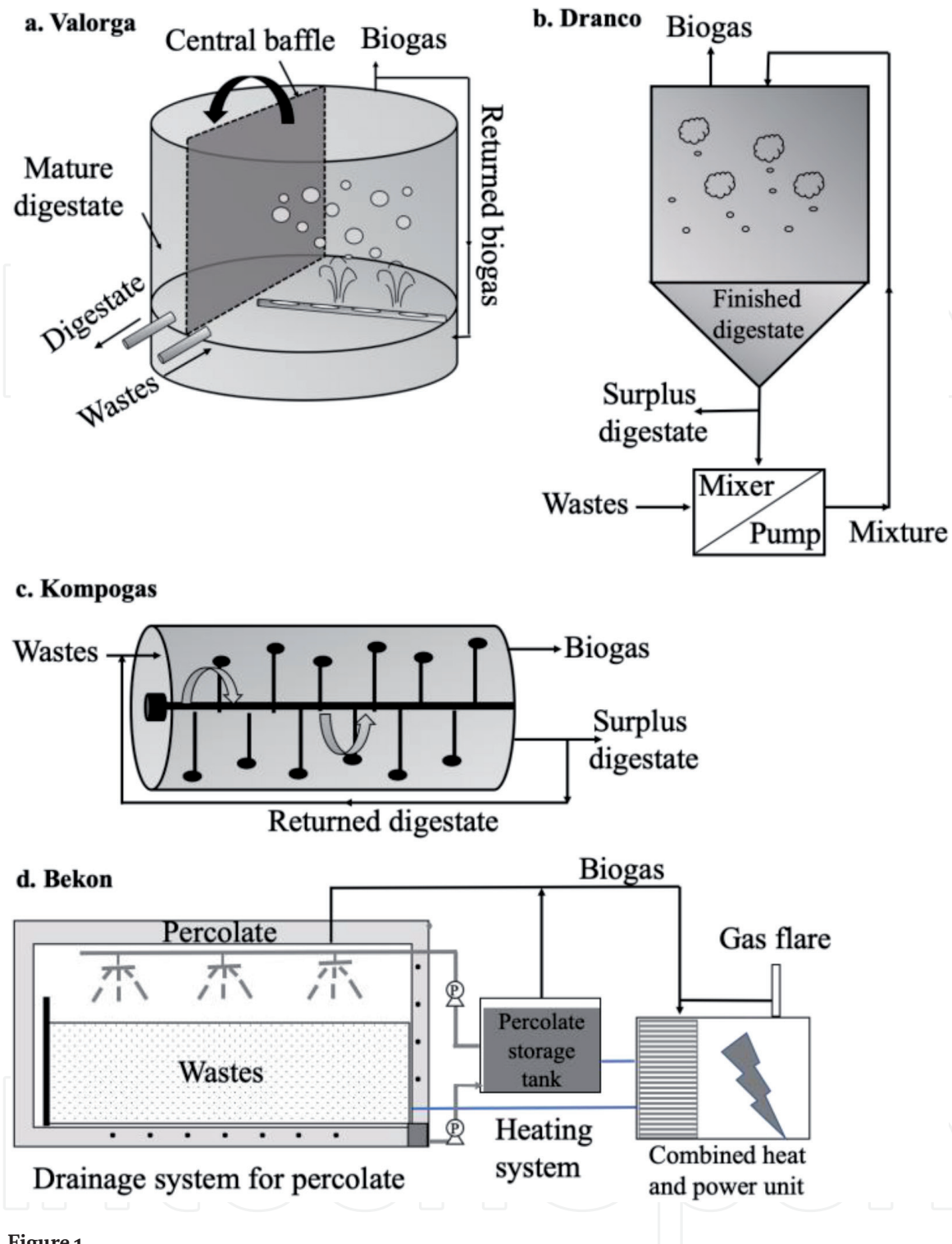


Figure 1.
 Dry anaerobic digester designs.

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 m³/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 $327 \text{ L kg}^{-1} \text{ VS}$ 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. $250 \text{ L g}^{-1} \text{ COD}_{\text{added}}$ 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 NO₃⁻ 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.

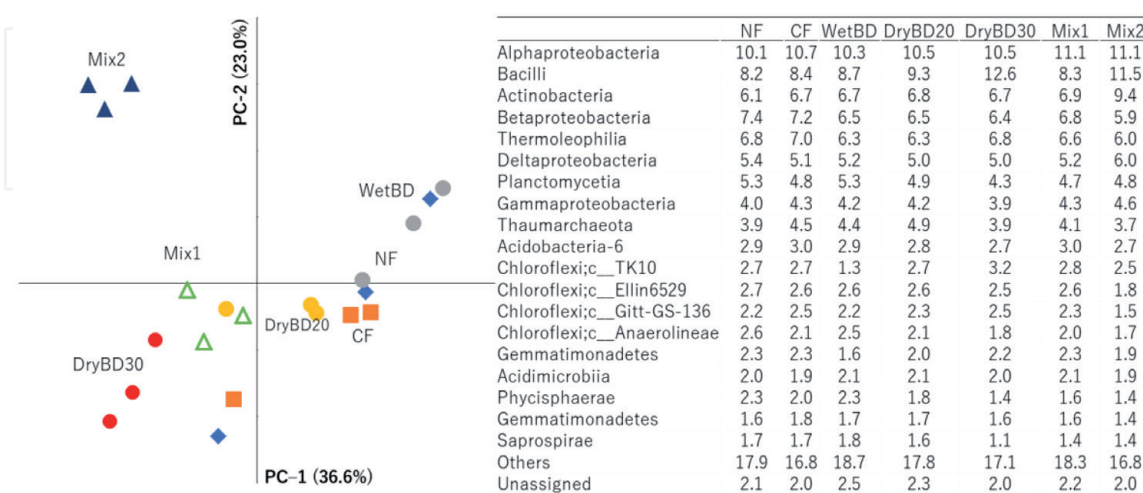


Figure 2. A Uni-Frac weighted PCA analysis of prokaryotic communities of soils with different amendments and incubated for 90 days. NF: no fertilizer, CF: chemical fertilizers, DryBD20: dry biogas digestate with an C/N ratio of 12, DryBD30: dry biogas digestate with an C/N ratio of 16, Mix1: DryBD20 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.

Acknowledgements

The study was supported by TUAT Collaboration Award 2019 and the Environment Research and Technology Development Fund (grant number: 1B-1103 and 1-1404) of the Ministry of the Environment, Japan.

Conflict of interest

The authors declare no conflict of interest.

Author details

Shohei Riya^{1*}, Lingyu Meng¹, Yuexi Wang², Chol Gyu Lee², Sheng Zhou³, Koki Toyota² and Masaaki Hosomi¹

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

IntechOpen

© 2020 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Mussoline W, Esposito G, Giordano A, Lens P. The anaerobic digestion of rice straw: A review. *Critical Reviews in Environmental Science and Technology*. 2013;**43**(9):895-915
- [2] Kumar R, Singh S, Singh OV. Bioconversion of lignocellulosic biomass: Biochemical and molecular perspectives. *Journal of Industrial Microbiology & Biotechnology*. 2008;**35**(5):377-391
- [3] Potter P, Ramankutty N, Bennett EM, Donner SD. Characterizing the spatial patterns of global fertilizer application and manure production. *Earth Interactions*. 2010;**14**:1-22
- [4] Schievano A, D'Imporzano G, Salati S, Adani F. On-field study of anaerobic digestion full-scale plants (part I): An on-field methodology to determine mass, carbon and nutrients balance. *Bioresource Technology*. 2011;**102**(17):7737-7744
- [5] Elsayed M, Abomohra A, Ai P, Wang DL, El-Mashad HM, Zhang YL. Biorefining of rice straw by sequential fermentation and anaerobic digestion for bioethanol and/or biomethane production: Comparison of structural properties and energy output. *Bioresource Technology*. 2018;**268**:183-189
- [6] Sawatdeenarunat C, Nguyen D, Surendra C, Shrestha S, Rajendran K, Oechsner H, et al. Anaerobic biorefinery: Current status, challenges, and opportunities. *Bioresource Technology*. 2016;**215**:304-313
- [7] Albuquerque JA, de la Fuente C, Ferrer-Costa A, Carrasco L, Cegarra J, Abad M, et al. Assessment of the fertiliser potential of digestates from farm and agroindustrial residues. *Biomass and Bioenergy*. 2012;**40**:181-189
- [8] Lal R. Carbon emission from farm operations. *Environment International*. 2004;**30**(7):981-990
- [9] Ge X, Xu F, Li Y. Solid-state anaerobic digestion of lignocellulosic biomass: Recent progress and perspectives. *Bioresource Technology*. 2016;**205**:239-249
- [10] Li Y, Park SY, Zhu J. Solid-state anaerobic digestion for methane production from organic waste. *Renewable and Sustainable Energy Reviews*. 2011;**15**(1):821-826
- [11] Logan M, Visvanathan C. Management strategies for anaerobic digestate of organic fraction of municipal solid waste: Current status and future prospects. *Waste Management & Research*. 2019;**37**:27-39
- [12] Angelonidi E, Smith SR. A comparison of wet and dry anaerobic digestion processes for the treatment of municipal solid waste and food waste. *Water Environment Journal*. 2015;**29**(4):549-557
- [13] Chiumenti A, da Borso F, Limina S. Dry anaerobic digestion of cow manure and agricultural products in a full-scale plant: Efficiency and comparison with wet fermentation. *Waste Management*. 2018;**71**:704-710
- [14] Moller HB, Sommer SG, Ahring BK. Separation efficiency and particle size distribution in relation to manure type and storage conditions. *Bioresource Technology*. 2002;**85**(2):189-196
- [15] Nkoa R. Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: A review. *Agronomy for Sustainable Development*. 2014;**34**(2):473-492
- [16] Riya S, Suzuki K, Meng L, Zhou S, Terada A, Hosomi M. The influence of the total solid content on the stability of dry-thermophilic anaerobic digestion of rice straw and pig manure. *Waste Management*. 2018;**76**:350-356

- [17] Zhou S, Nikolausz M, Zhang JN, Riya SH, Terada A, Hosomi M. Variation of the microbial community in thermophilic anaerobic digestion of pig manure mixed with different ratios of rice straw. *Journal of Bioscience and Bioengineering*. 2016;**122**(3):334-340
- [18] Möller K, Müller T. Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review. *Engineering in Life Sciences*. 2012;**12**(3):242-257
- [19] Rajagopal R, Masse DI, Singh G. A critical review on inhibition of anaerobic digestion process by excess ammonia. *Bioresource Technology*. 2013;**143**:632-641
- [20] Fernandes TV, Keesman KJ, Zeeman G, van Lier JB. Effect of ammonia on the anaerobic hydrolysis of cellulose and tributyrin. *Biomass and Bioenergy*. 2012;**47**:316-323
- [21] Kayhanian M. Ammonia inhibition in high-solids biogasification: An overview and practical solutions. *Environmental Technology*. 1999;**20**(4):355-365
- [22] Li Y, Zhu J, Wan C, Park SY. Solid-state anaerobic digestion of corn stover for biogas production. *Transactions of the Asabe*. 2011;**54**(4):1415-1421
- [23] Abouelenien F, Namba Y, Kosseva MR, Nishio N, Nakashimada Y. Enhancement of methane production from co-digestion of chicken manure with agricultural wastes. *Bioresource Technology*. 2014;**159**:80-87
- [24] Abouelenien F, Kitamura Y, Nishio N, Nakashimada Y. Dry anaerobic ammonia-methane production from chicken manure. *Applied Microbiology and Biotechnology*. 2009;**82**(4):757-764
- [25] Li YQ, Zhang RH, Chen C, Liu GQ, He YF, Liu XY. Biogas production from co-digestion of corn Stover and chicken manure under anaerobic wet, hemi-solid, and solid state conditions. *Bioresource Technology*. 2013;**149**:406-412
- [26] Zhou Y, Li C, Nges IA, Liu J. The effects of pre-aeration and inoculation on solid-state anaerobic digestion of rice straw. *Bioresource Technology*. 2017;**224**:78-86
- [27] Meng LY, Xie L, Kinh CT, Suenaga T, Hori T, Riya S, et al. Influence of feedstock-to-inoculum ratio on performance and microbial community succession during solid-state thermophilic anaerobic co-digestion of pig urine and rice straw. *Bioresource Technology*. 2018;**252**:127-133
- [28] Li YY, Wang YQ, Yu ZH, Lu JX, Li DY, Wang GY, et al. Effect of inoculum and substrate/inoculum ratio on the performance and methanogenic archaeal community structure in solid state anaerobic co-digestion of tomato residues with dairy manure and corn Stover. *Waste Management*. 2018;**81**:117-127
- [29] Ma XG, Jiang T, Chang JL, Tang Q, Luo T, Cui ZJ. Effect of substrate to inoculum ratio on biogas production and microbial community during hemi-solid-state batch anaerobic Co-digestion of rape straw and dairy manure. *Applied Biochemistry and Biotechnology*. 2019;**189**(3):884-902
- [30] Cui ZF, Shi J, Li YB. Solid-state anaerobic digestion of spent wheat straw from horse stall. *Bioresource Technology*. 2011;**102**(20):9432-9437
- [31] Suksong W, Kongjan P, Prasertsan P, Imai T, O-Thong S. Optimization and microbial community analysis for production of biogas from solid waste residues of palm oil mill industry by solid-state anaerobic digestion. *Bioresource Technology*. 2016;**214**:166-174

- [32] Chen Y, Wen Y, Zhou JW, Xu C, Zhou Q. Effects of pH on the hydrolysis of lignocellulosic wastes and volatile fatty acids accumulation: The contribution of biotic and abiotic factors. *Bioresource Technology*. 2012;**110**:321-329
- [33] Xu FQ, Wang ZW, Tang L, Li YB. A mass diffusion-based interpretation of the effect of total solids content on solid-state anaerobic digestion of cellulosic biomass. *Bioresource Technology*. 2014;**167**:178-185
- [34] Le Hyaric R, Benbelkacem H, Bollon J, Bayard R, Escudie R, Buffiere P. Influence of moisture content on the specific methanogenic activity of dry mesophilic municipal solid waste digestate. *Journal of Chemical Technology and Biotechnology*. 2012;**87**(7):1032-1035
- [35] Bollon J, Benbelkacem H, Gourdon R, Buffiere P. Measurement of diffusion coefficients in dry anaerobic digestion media. *Chemical Engineering Science*. 2013;**89**:115-119
- [36] Abbassi-Guendouz A, Brockmann D, Trably E, Dumas C, Delgenes J-P, Steyer J-P, et al. Total solids content drives high solid anaerobic digestion via mass transfer limitation. *Bioresource Technology*. 2012;**111**:55-61
- [37] Zhu J, Yang L, Li Y. Comparison of premixing methods for solid-state anaerobic digestion of corn Stover. *Bioresource Technology*. 2015;**175**:430-435
- [38] Degueurce A, Tomas N, Le Roux S, Martinez J, Peu P. Biotic and abiotic roles of leachate recirculation in batch mode solid-state anaerobic digestion of cattle manure. *Bioresource Technology*. 2016;**200**:388-395
- [39] Andre L, Pauss A, Ribeiro T. Solid anaerobic digestion: State-of-art, scientific and technological hurdles. *Bioresource Technology*. 2018;**247**:1027-1037
- [40] Lei ZF, Zhang ZY, Huang WW, Cai W. Recent Progress on dry anaerobic digestion of organic solid wastes: Achievements and challenges. *Current Organic Chemistry*. 2015;**19**(5):400-412
- [41] Rapport J, Zhang R, Jenkins B, Williams R. *Current Anaerobic Digestion Technologies Used for Treatment of Municipal Organic Solid Waste*. Davis: University of California; Contractor Report to the California Integrated Waste Management Board; 2008
- [42] Valorga, References I. Available from: <http://www.valorgainternational.fr/en/pag8-OUR-REFERENCES.html>
- [43] de Laclos HF, Desbois S, Saint-Joly C. Anaerobic digestion of municipal solid organic waste: Valorga full-scale plant in Tilburg, the Netherlands. *Water Science and Technology*. 1997;**36**(6-7):457-462
- [44] Angelidaki I, Ellegaard L, Ahring B. *Applications of the Anaerobic Digestion Process*. Berlin, Heidelberg: Springer; 2003
- [45] Nichols C. Overview of anaerobic digestion technologies in Europe. *BioCycle*. 2004;**45**(1):47-53
- [46] Fu YR, Luo T, Mei ZL, Li J, Qiu K, Ge YH. Dry anaerobic digestion technologies for agricultural straw and acceptability in China. *Sustainability*. 2018;**10**(12):4588
- [47] Bekon. *Generating Energy from Biomass*. Available from: <https://www.bekon.eu/en/generating-energy-from-biomass/>
- [48] Zeshan, Karthikeyan OP, Visvanathan C. Effect of C/N ratio and ammonia-N accumulation in a

- pilot-scale thermophilic dry anaerobic digester. *Bioresource Technology*. 2012;**113**:294-302
- [49] Kim DH, Oh SE. Continuous high-solids anaerobic co-digestion of organic solid wastes under mesophilic conditions. *Waste Management*. 2011;**31**(9-10):1943-1948
- [50] Benbelkacem H, Bayard R, Abdelhay A, Zhang Y, Gourdon R. Effect of leachate injection modes on municipal solid waste degradation in anaerobic bioreactor. *Bioresource Technology*. 2010;**101**(14):5206-5212
- [51] Meng L, Maruo K, Xie L, Riya S, Terada A, Hosomi M. Comparison of leachate percolation and immersion using different inoculation strategies in thermophilic solid-state anaerobic digestion of pig urine and rice straw. *Bioresource Technology*. 2019;**277**:216-220
- [52] Andre L, Durante M, Pauss A, Lespinard O, Ribeiro T, Lamy E. Quantifying physical structure changes and non-uniform water flow in cattle manure during dry anaerobic digestion process at lab scale: Implication for biogas production. *Bioresource Technology*. 2015;**192**:660-669
- [53] Karthikeyan OP, Visvanathan C. Bio-energy recovery from high-solid organic substrates by dry anaerobic bio-conversion processes: A review. *Reviews in Environmental Science and Bio-Technology*. 2013;**12**(3):257-284
- [54] Forster-Carneiro T, Perez M, Romero LI, Sales D. Dry-thermophilic anaerobic digestion of organic fraction of the municipal solid waste: Focusing on the inoculum sources. *Bioresource Technology*. 2007;**98**(17):3195-3203
- [55] Yang L, Xu F, Ge X, Li Y. Challenges and strategies for solid-state anaerobic digestion of lignocellulosic biomass. *Renewable and Sustainable Energy Reviews*. 2015;**44**:824-834
- [56] Shi J, Xu FQ, Wang ZJ, Stiverson JA, Yu ZT, Li YB. Effects of microbial and non-microbial factors of liquid anaerobic digestion effluent as inoculum on solid-state anaerobic digestion of corn Stover. *Bioresource Technology*. 2014;**157**:188-196
- [57] Xu FQ, Wang F, Lin L, Li YB. Comparison of digestate from solid anaerobic digesters and dewatered effluent from liquid anaerobic digesters as inocula for solid state anaerobic digestion of yard trimmings. *Bioresource Technology*. 2016;**200**:753-760
- [58] Li Y, Zhu J, Wan C. Combined liquid to solid-phase anaerobic digestion for methane production from municipal and agricultural wastes. United States. 2014. Patent No. US 8,771,980 B2
- [59] Makádi M, Tomócsik A, Orosz V. Digestate: A New Nutrient Source-Review. *IntechOpen: Biogas*; 2012
- [60] Alburquerque JA, de la Fuente C, Bernal MP. Chemical properties of anaerobic digestates affecting C and N dynamics in amended soils. *Agriculture, Ecosystems and Environment*. 2012;**160**:15-22
- [61] Beni C, Servadio P, Marconi S, Neri U, Aromolo R, Diana G. Anaerobic digestate administration: Effect on soil physical and mechanical behavior. *Communications in Soil Science and Plant Analysis*. 2012;**43**(5):821-834
- [62] Garg RN, Pathak H, Das D, Tomar R. Use of flyash and biogas slurry for improving wheat yield and physical properties of soil. *Environmental Monitoring and Assessment*. 2005;**107**(1-3):1-9
- [63] Arthurson V. Closing the global energy and nutrient cycles through application of biogas residue to agricultural land—potential benefits and drawback. *Energies*. 2009;**2**(2):226-242

- [64] Sreekrishnan T, Kohli S, Rana V. Enhancement of biogas production from solid substrates using different techniques—A review. *Bioresource Technology*. 2004;**95**(1):1-10
- [65] Scherr KE, Lundaa T, Klose V, Bochmann G, Loibner AP. Changes in bacterial communities from anaerobic digesters during petroleum hydrocarbon degradation. *Journal of Biotechnology*. 2012;**157**(4):564-572
- [66] Ziemiński K, Frąc M. Methane fermentation process as anaerobic digestion of biomass: Transformations, stages and microorganisms. *African Journal of Biotechnology*. 2012;**11**(18):4127-4139
- [67] Insam H, Gómez-Brandón M, Ascher J. Manure-based biogas fermentation residues—friend or foe of soil fertility? *Soil Biology and Biochemistry*. 2015;**84**:1-14
- [68] Cheng J, Chen Y, He T, Liao R, Liu R, Yi M, et al. Soil nitrogen leaching decreases as biogas slurry DOC/N ratio increases. *Applied Soil Ecology*. 2017;**111**:105-113
- [69] Sängler A, Geisseler D, Ludwig B. Effects of moisture and temperature on greenhouse gas emissions and C and N leaching losses in soil treated with biogas slurry. *Biology and Fertility of Soils*. 2011;**47**(3):249-259
- [70] Svoboda N, Taube F, Wienforth B, Kluß C, Kage H, Herrmann A. Nitrogen leaching losses after biogas residue application to maize. *Soil and Tillage Research*. 2013;**130**:69-80
- [71] Bicudo JR, Goyal SM. Pathogens and manure management systems: A review. *Environmental Technology*. 2003;**24**(1):115-130
- [72] Hutchison M, Walters LD, Avery S, Munro F, Moore A. Analyses of livestock production, waste storage, and pathogen levels and prevalences in farm manures. *Applied and Environmental Microbiology*. 2005;**71**(3):1231-1236
- [73] Amlinger F, Götz B, Dreher P, Geszti J, Weissteiner C. Nitrogen in biowaste and yard waste compost: Dynamics of mobilisation and availability—A review. *European Journal of Soil Biology*. 2003;**39**(3):107-116
- [74] Johansen A, Carter MS, Jensen ES, Hauggard-Nielsen H, Ambus P. Effects of digestate from anaerobically digested cattle slurry and plant materials on soil microbial community and emission of CO₂ and N₂O. *Applied Soil Ecology*. 2013;**63**:36-44
- [75] Sängler A, Geisseler D, Ludwig B. C and N dynamics of a range of biogas slurries as a function of application rate and soil texture: A laboratory experiment. *Archives of Agronomy and Soil Science*. 2014;**60**(12):1779-1794
- [76] Sawada K, Toyota K. Effects of the application of Digestates from wet and dry anaerobic fermentation to Japanese Paddy and Upland soils on short-term nitrification. *Microbes and Environments*. 2015;**30**(1):37-43
- [77] Goberna M, Podmirseg SM, Waldhuber S, Knapp BA, García C, Insam H. Pathogenic bacteria and mineral N in soils following the land spreading of biogas digestates and fresh manure. *Applied Soil Ecology*. 2011;**49**:18-25
- [78] Cavalli D, Corti M, Baronchelli D, Bechini L, Marino Gallina P. CO₂ emissions and mineral nitrogen dynamics following application to soil of undigested liquid cattle manure and digestates. *Geoderma*. 2017;**308**:26-35
- [79] Gómez-Brandón M, Juárez MF-D, Zangerle M, Insam H. Effects of digestate on soil chemical and

microbiological properties: A comparative study with compost and vermicompost. *Journal of Hazardous Materials*. 2016;**302**:267-274

[80] Viaene J, Agneessens L, Capito C, Ameloot N, Reubens B, Willekens K, et al. Co-ensiling, co-composting and anaerobic co-digestion of vegetable crop residues: Product stability and effect on soil carbon and nitrogen dynamics. *Scientia Horticulturae*. 2017;**220**:214-225

[81] Herrmann A, Kage H, Taube F, Sieling K. Effect of biogas digestate, animal manure and mineral fertilizer application on nitrogen flows in biogas feedstock production. *European Journal of Agronomy*. 2017;**91**:63-73

[82] Wang Y, Chikamatsu S, Gegen T, Sawada K, Toyota K, Riya S, et al. Application of biogas digestate with rice straw mitigates nitrate leaching potential and suppresses root-knot nematode (*Meloidogyne incognita*). *Agronomy*. 2019;**9**(5):227

[83] Stumborg C, Schoenau JJ, Malhi SS. Nitrogen balance and accumulation pattern in three contrasting prairie soils receiving repeated applications of liquid swine and solid cattle manure. *Nutrient Cycling in Agroecosystems*. 2007;**78**(1):15-25

[84] Rigby H, Smith SR. Nitrogen availability and indirect measurements of greenhouse gas emissions from aerobic and anaerobic biowaste digestates applied to agricultural soils. *Waste Management*. 2013;**33**(12):2641-2652

[85] Di HJ, Cameron KC. Nitrate leaching in temperate agroecosystems: Sources, factors and mitigating strategies. *Nutrient Cycling in Agroecosystems*. 2002;**64**(3):237-256

[86] Pansu M, Thuriès L. Kinetics of C and N mineralization, N immobilization

and N volatilization of organic inputs in soil. *Soil Biology and Biochemistry*. 2003;**35**(1):37-48

[87] Yanni SF, Whalen JK, Simpson MJ, Janzen HH. Plant lignin and nitrogen contents control carbon dioxide production and nitrogen mineralization in soils incubated with Bt and non-Bt corn residues. *Soil Biology and Biochemistry*. 2011;**43**(1):63-69

[88] Hoyle FC, Murphy DV. Influence of organic residues and soil incorporation on temporal measures of microbial biomass and plant available nitrogen. *Plant and Soil*. 2011;**347**(1-2):53

[89] Puttaso A, Vityakon P, Saenjan P, Trelo-Ges V, Cadisch G. Relationship between residue quality, decomposition patterns, and soil organic matter accumulation in a tropical sandy soil after 13 years. *Nutrient Cycling in Agroecosystems*. 2011;**89**(2):159-174

[90] Trinsoutrot I, Recous S, Bentz B, Lineres M, Cheneby D, Nicolardot B. Biochemical quality of crop residues and carbon and nitrogen mineralization kinetics under nonlimiting nitrogen conditions. *Soil Science Society of America Journal*. 2000;**3**(64):918-926. Available from: <https://doi.org/10.2136/sssaj2000.643918x>

[91] Demiraj E, Libutti A, Malltezi J, Rroço E, Brahushi F, Monteleone M, et al. Effect of organic amendments on nitrate leaching mitigation in a sandy loam soil of Shkodra district, Albania. *Italian Journal of Agronomy*. 2018;**13**(1):93-102

[92] Gai X, Liu H, Liu J, Zhai L, Wang H, Yang B, et al. Contrasting impacts of long-term application of manure and crop straw on residual nitrate-N along the soil profile in the North China plain. *Science of The Total Environment*. 2019;**650**:2251-2259

[93] Shindo H, Nishio T. Immobilization and remineralization

of N following addition of wheat straw into soil: Determination of gross N transformation rates by ¹⁵N-ammonium isotope dilution technique. *Soil Biology and Biochemistry*. 2005;**37**(3):425-432

[94] Yang S, Wang Y, Liu R, Xing L, Yang Z. Improved crop yield and reduced nitrate nitrogen leaching with straw return in a rice-wheat rotation of Ningxia irrigation district. *Scientific Reports*. 2018;**8**(1):9458

[95] Pan F-F, Yu W-T, Ma Q, Zhou H, Jiang C-M, Xu Y-G, et al. Influence of ¹⁵N-labeled ammonium sulfate and straw on nitrogen retention and supply in different fertility soils. *Biology and Fertility of Soils*. 2017;**53**(3):303-313

[96] Aulakh M, Walters D, Doran J, Francis D, Mosier A. Crop residue type and placement effects on denitrification and mineralization. *Soil Science Society of America Journal*. 1991;**55**(4):1020-1025

[97] Chen B, Liu E, Tian Q, Yan C, Zhang Y. Soil nitrogen dynamics and crop residues. A review. *Agronomy for Sustainable Development*. 2014;**34**(2):429-442

[98] Nicolardot B, Chaussod R, Cheneby D, Baugnet M. Effects of some factors on immobilization and remineralization of nitrogen in soils. In: *Stable Isotopes in Plant Nutrition, Soil Fertility and Environmental Studies*. Proceedings of an International Symposium on the Use of Stable Isotopes in Plant Nutrition, Soil Fertility and Environmental Studies. Vienna: IAEA, FAO; 1991. pp. 327-330. https://inis.iaea.org/search/search.aspx?orig_q=RN:220889251991

[99] Delgado J. Quantifying the loss mechanisms of nitrogen. *Journal of Soil and Water Conservation*. 2002;**57**(6):389-398

[100] Yadvinder S, Gupta RK, Gurpreet S, Jagmohan S, Sidhu HS, Bijay S. Nitrogen and residue management effects on agronomic productivity and nitrogen use efficiency in rice-wheat system in Indian Punjab. *Nutrient Cycling in Agroecosystems*. 2009;**84**(2):141-154

[101] Zhao Y, Zhang J, Müller C, Cai Z. Temporal variations of crop residue effects on soil N transformation depend on soil properties as well as residue qualities. *Biology and Fertility of Soils*. 2018;**54**(5):659-669

[102] Kayani MZ, Mukhtar T, Hussain MA. Effects of southern root knot nematode population densities and plant age on growth and yield parameters of cucumber. *Crop Protection*. 2017;**92**:207-212

[103] Ralmi NHAA, Khandaker MM, Mat N. Occurrence and control of root knot nematode in crops: A review. *Australian Journal of Crop Science*. 2016;**11**(12):1649

[104] Yadav U. Recent trends in nematode management practices: The Indian context. *International Research Journal of Engineering and Technology*. 2017;**12**:482-489

[105] Eisenback JD, Triantaphyllou HH. Root-knot nematodes: *Meloidogyne* species and races. *Manual of Agricultural Nematology*. 1991;**1**:191-274

[106] Hunt DJ, Handoo ZA. Taxonomy, identification and principal species. *Root-knot Nematodes*. 2009;**1**:55-88

[107] Fujimoto T, Hasegawa S, Otake K, Mizukubo T. Effect of water flow on the mobility of the root-knot nematode *Meloidogyne incognita* in columns filled with glass beads, sand or andisol. *Applied Soil Ecology*. 2009;**43**(2-3):200-205

[108] Seo Y, Kim YH. Control of *Meloidogyne incognita* using mixtures

of organic acids. The Plant Pathology Journal. 2014;**30**(4):450

[109] Shah SJ, Anjam MS, Mendy B, Anwer MA, Habash SS, Lozano-Torres JL, et al. Damage-associated responses of the host contribute to defence against cyst nematodes but not root-knot nematodes. Journal of Experimental Botany. 2017;**68**(21-22):5949-5960

[110] Castagnone-Sereno P, Kermarrec A. Invasion of tomato roots and reproduction of *Meloidogyne incognita* as affected by raw sewage sludge. Journal of Nematology. 1991;**23**(4S):724

[111] Nico AI, Jiménez-Díaz RM, Castillo P. Control of root-knot nematodes by composted agro-industrial wastes in potting mixtures. Crop Protection. 2004;**23**(7):581-587

[112] Mahran A, Conn K, Tenuta M, Lazarovits G, Daayf F. Effectiveness of liquid hog manure and acidification to kill *Pratylenchus* spp. in soil. Journal of Nematology. 2008;**40**(4):266

[113] Hallmann J, Rodríguez-Kábana R, Kloepper JW. Chitin-mediated changes in bacterial communities of the soil, rhizosphere and within roots of cotton in relation to nematode control. Soil Biology and Biochemistry. 1999;**31**(4):551-560

[114] Mcsorley R. Overview of organic amendments for management of plant-parasitic nematodes, with case studies from Florida. Journal of Nematology. 2011;**43**(2):69

[115] Jothi G, Pugalendhi S, Poornima K, Rajendran G. Management of root-knot nematode in tomato *Lycopersicon esculentum*, mill., with biogas slurry. Bioresource Technology. 2003;**89**(2):169-170

[116] Westphal A, Kücke M, Heuer H. Soil amendment with digestate from

bio-energy fermenters for mitigating damage to *Beta vulgaris* subsp. By *Heterodera schachtii*. Applied Soil Ecology. 2016;**99**:129-136

[117] Bulluck Iii L, Barker K, Ristaino J. Influences of organic and synthetic soil fertility amendments on nematode trophic groups and community dynamics under tomatoes. Applied Soil Ecology. 2002;**21**(3):233-250

[118] Korayem A. Effect of some organic wastes on *Meloidogyne incognita* development and tomato tolerance to the nematode. Egyptian Journal of Phytopathology. 2003;**31**(1-2):119-127

[119] Renčo M. Organic amendments of soil as useful tools of plant parasitic nematodes control. Helminthologia. 2013;**50**(1):3-14

[120] Agu C. Effects of organic manure types on root-gall nematode disease and African yam bean yield. Journal of American Science. 2008;**4**(1):76-79

[121] Akhtar M, Malik A. Roles of organic soil amendments and soil organisms in the biological control of plant-parasitic nematodes: A review. Bioresource Technology. 2000;**74**(1):35-47

[122] Garcia-Sánchez M, Garcia-Romera I, Cajthaml T, Tlustoš P, Száková J. Changes in soil microbial community functionality and structure in a metal-polluted site: The effect of digestate and fly ash applications. Journal of Environmental Management. 2015;**162**:63-73

[123] Gielnik A, Pechaud Y, Huguenot D, Cébron A, Riou J-M, Guibaud G, et al. Effect of digestate application on microbial respiration and bacterial communities' diversity during bioremediation of weathered petroleum hydrocarbons contaminated soils. Science of The Total Environment. 2019;**670**:271-281

[124] Hupfauf S, Bachmann S, Juárez MF-D, Insam H, Eichler-Löbermann B. Biogas digestates affect crop P uptake and soil microbial community composition. *The Science of the Total Environment*. 2016;**542**:1144-1154

[125] Yeates G. Predation by *Mononchoides potohikus* (Nematoda: Diplogasteridae) in laboratory culture. *Nematologica*. 1969;**15**(1):1-9

[126] Esser R. Biological Control of Nematodes by Nematodes: Dorylaims (Nematoda: Dorylaimina). I. Gainesville: Fla. Department Agric. & Consumer Serv., Division of Plant Industry; 1987

[127] Yeates G. Soil nematode populations depressed in the presence of earthworms. *Pedobiologia*. 1981;**22**(1):191-195

[128] Wang K-H, Sipes B, Schmitt D. Suppression of *Rotylenchulus reniformis* by *Crotalaria juncea*, *Brassica napus*, and *Tagetes erecta*. *Nematropica*. 2001;**31**(2):235-249

[129] Wang K-H, Sipes B, Schmitt D. Management of *Rotylenchulus reniformis* in pineapple, *Ananas comosus*, by intercycle cover crops. *Journal of Nematology*. 2002;**34**(2):106

[130] Bordallo J, Lopez-Llorca L, Jansson HB, Salinas J, Persmark L, Asensio L. Colonization of plant roots by egg-parasitic and nematode-trapping fungi. *The New Phytologist*. 2002;**154**(2):491-499

[131] Jaffee B, Ferris H, Scow K. Nematode-trapping fungi in organic and conventional cropping systems. *Phytopathology*. 1998;**88**(4):344-350