Pyrolysis coupled anaerobic digestion process for food waste and recalcitrant residues: Fundamentals, challenges, and considerations

Abdulmoseen Segun Giwa1,2 | Heng Xu2,3 | Fengmin Chang2 | Xiaoqian Zhang4 | Nasir Ali5 | Jing Yuan1 | Kaijun Wang2

Abstract
Food waste (FW) is a severe environmental problem all over the world, and the recalcitrant organic residues (ROR) from FW treatment plant operations are also a critical environmental issue due to unsustainable treatment and disposal techniques. Requirements for FW and ROR complete exploitation with the establishment of recycling-renewable technologies are very crucial. This paper review AD and pyrolysis as two promising technologies to degrade FW and its residues, creating numerous renewable bioenergy yields with value-added. Existing oil/tar application methods in the AD suffered from various problems such as microorganism toxicity and limited productivity. Future upgrading techniques considering the second-stage pyrolysis process to decompose oil/tars for syngas with high hydrogen content and enhanced bio-methanation in the AD were addressed. Simultaneous pyrolysis by-product recycle in the AD during the valorization of FW are aimed to have the features of sustainability toward increased bioenergy production, reactor efficiency, and agricultural application.

Keywords
anaerobic digestion, coupling, food waste, pyrolysis, recalcitrant organic residues
INTRODUCTION

Globally, the rapid rise in population combined with increasing industrialization has enhanced the continuous generation of food waste (FW). In reference to studies from the Food and Agricultural Organization (FAO), global annual food production accrued to approximately 1.3 billion tons/y, thus representing one third of the worldwide annual food production. It has been assumed that FW increase trend might continue shortly by 44% from 2005 to 2025 due to population growth and economic trend, with much projection toward developing countries. China's FW production volume has overtaken most of the European countries, while the FW in most European countries is envisaged to rise from 89 million tons in 2006-126 million tons in 2020. FW is the largest component of municipal solid waste (MSW); China MSW accounted for about 50% FW with 245 000 tons per day of FW generated. FW production in China as at 2017 reached 97.72 million tons, and conventional techniques for the treatment of FW are no longer considered viable due to the environmental challenges, high moisture content, low calorific value, perishability, and the need for sustainable recovery. Among several traditional methods such as landfilling and incineration, anaerobic digestion (AD) has been considered to be much sustainable and economical for resource recovery. AD process with the aid of biological microorganism can convert FW to products with additional value as organic fertilizer and soil emulsifier with modest methods and low-cost tendency.

It was reported in the year 2011 that FW was rated third among fifteen identified potential resource opportunities, due to it is heterogeneous and as sources for availability of different valuable chemicals and additives. Nevertheless, a conventional FW processing facility generates 30% of recalcitrant organic residues (ROR) from the total FW material during biological treatment with the AD. Typically, these ROR are assumed solitarly as unusable waste disposed of mostly through uneconomical incineration and landfilling techniques. The perception from bioenergy recovery demands the necessity to explore an appropriate economical route to utilize these plentiful ROR. This will not only reduce the severe environmental influences but also offer an improved recycling level and additional monetary paybacks to FW processing facility. Pyrolysis, which is a thermochemical treatment process, can accomplish a better outcome in the treatment of ROR that is problematic to biodegradable and plastic wastes. Pyrolysis is the disintegration of organic matters via a thermal process in an oxygen-free environment to yield solid (biochar), noncondensable gaseous matters, and bio-oil. Disposal via thermochemical process “pyrolysis” has been previously reported for typical properties (Table 1) of individual waste fractions that can be found in peculiar wastes such as ROR or difficult biodegradable fractions. The LHV of the ROR acquired through the weighted superposition of LHV's of single constituents is around 15.72 MJ/kg; it exhibits boundless potential as pyrolysis feedstock.

Recent studies have shown that introducing of biochar as additives in AD can enhance the formation of the biofilm and improve the output of bio-methane to 5%-31%. Besides, second-stage pyrolysis decomposition of the ROR and subsequent oil/tar to syngas can find a route of utilization in AD, thus avoiding direct usage of oil/tar that can pose as toxicants to AD microbes. Integrated or combined proposed routes for FW and associated residues treatment during the past few years are scarcely available, except studies on pyrolysis integrated with AD of only FW, biomass, and sludge treatment. Presently, there is no single review with emphasis on the holistic treatment and disposal of FW and the ROR via coupling pyrolysis and AD simultaneously. This technique incorporates resource recovery approaches via simultaneous holistic valorization of the FW and the ROR. We, therefore, consider this review to be a timely contribution to encourage further research and development in this field for establishments of sustainable routes for FW and associated ROR treatment via coupling pyrolysis and AD.

This review focuses on the status of FW globally and conventional FW treatment techniques. It reviews some of the fundamentals of anaerobic and pyrolysis technologies based on existing knowledge, the primary factors associated with each technology as a single process, with the emphasis on process stability. Besides, this review provides an insight into the challenges related to the global application of AD treatment plants of FW.

Finally, this paper deliberates on sustainable routes for FW treatment and the ROR through the pyrolysis and AD coupled as a new concept appearing in recent years. It addresses high syngas for bio-methanation from the oil in a second-stage...
Table 2 presents the characteristics of FW in some countries. Chinese FW as compared to Korean and the United Kingdom was reported to contain high water content in the range of 80%-90%, contains high amounts of lipid 1%-5%, high salt contents 1%-3%, and some complex composition materials such as plastic, papers, metals, and glass.

Proper management and treatment challenges to reuse or recycle FW have been a bottleneck. These disorderly management and treatment techniques bring along problems that pollute the environment, spread diseases, create filthy surroundings, sanitation, health, and safety problems.

2.2 China status quo and global food waste treatment techniques

Because of FW complex nature, it has been reckoned with features of high moisture, salinity, and organic and oil content, which is different from common MSW; hence, it will require different methods of treatment. Valuable resources are obtainable when FW is managed reasonably and effectively, reducing the environmental impact. Also, FW has potential resources for utilization if properly harnessed.

The European Union instituted a long-term determined goal for the implementation of a modest low carbon economy in 2050, and projected to achieve 80%-95% greenhouse gas emission minimization by 2050. Further biofuel production limit of 7% from FW and feed crops for biofuel production as energy in transport in the Member States in 2020 has been instructed. The goal is to replace fossil fuel utilization on a huge scale as a bio-based green economy that plays vital role not only for energy purposes, but also for material applications and valuable chemicals.

2.1 Properties and environmental issues of food waste

Food waste, an essential component of MSW, is heterogeneous; it consists of solid food residues and several kinds of oil–water blends such as vegetable and animal fat or oil, which is not appropriate for ingesting. The composition of raw FW analyzed on a dry basis also consists of cellulose (36.9%, w/v), hemicellulose (26.6%, w/v), lignin materials (12.6%, w/v), and soluble water (23.9%, w/v), respectively. The FW generated from processing industries is simpler to recycle and transform due to their easy and uniform composition. Table 2 presents the characteristics of FW in some countries. Chinese FW as compared to Korean and the United Kingdom was reported to contain high water content in the range of 80%-90%, contains high amounts of lipid 1%-5%, high salt contents 1%-3%, and some complex composition materials such as plastic, papers, metals, and glass.

Proper management and treatment challenges to reuse or recycle FW have been a bottleneck. These disorderly management and treatment techniques bring along problems that pollute the environment, spread diseases, create filthy surroundings, sanitation, health, and safety problems.

2.2 China status quo and global food waste treatment techniques

Because of FW complex nature, it has been reckoned with features of high moisture, salinity, and organic and oil content, which is different from common MSW; hence, it will require different methods of treatment. Valuable resources are obtainable when FW is managed reasonably and effectively, reducing the environmental impact. Also, FW has potential resources for utilization if properly harnessed.

The European Union instituted a long-term determined goal for the implementation of a modest low carbon economy in 2050, and projected to achieve 80%-95% greenhouse gas emission minimization by 2050. Further biofuel production limit of 7% from FW and feed crops for biofuel production as energy in transport in the Member States in 2020 has been instructed. The goal is to replace fossil fuel utilization on a huge scale as a bio-based green economy that plays vital role not only for energy purposes, but also for material applications and valuable chemicals.
According to Statista, the amount of FW generation from 1990 to 2017 in China accrued to approximately 215.21 million tons with the largest amount of FW being generated in Guangdong province in the southern part of China with approximately 23.9 million tons in the year 2016. Several treatment techniques have been proposed to effectively manage and redress existing environmental problems posed by FW management in China via low-cost techniques. China’s 13th Five-Year Plan goal for the implementation of national urban solid waste disposal facilities is to construct extra FW processing and resource deployment facilities and enlargement of FW capacity treatment by the end of 2020 to 34 400 t d⁻¹. The government implemented 100 demonstration projects for FW treatment and disposal; AD is the commonly adopted FW treatment methods (with over 90% use rate for FW treatment). Accompanying reasons are because of its economic, social, and environmental benefits. It can also produce digestates for the application on fields to improve farming and even energy such as heat, power, and natural gas, depending on the configuration of the AD plant. Several popular treatment methods are commonly applied globally. These are silage/forage production, composting (or organic fertilizer), fast composting, AD, landfill, and incineration.

### 2.2.1 Landfill

Food waste is proven as a critical factor contributing to global climate change. The disposal of FW in the landfill emits a large volume of methane and carbon dioxide. The landfill biogas is mostly made up of methane with about 40%-70% by dry volume. The methane gas has warming effects stronger than carbon dioxide by about 20-25 times. Landfills are the primary means of MSW disposal in China; at the end of 2013, almost 70% of household waste was being deposited in landfills. The environmental effect such as leachate to underground water sources and odor is associated with problems with this technique. For varieties of FW disposed of via landfill, highest emissions often occur, even with methane capture; Moult et al recommended the use of FW as animal feed and mitigation for bread and fish via AD rather than disposal of with landfill.

### 2.2.2 Incineration

It involves the complete oxidation of the waste in an excess supply of oxygen to produce carbon dioxide, water, and ash, plus some other products such as metals, trace hydrocarbons, and acid gases. Incineration has shown a good option in terms of energy recovery and waste stream reduction compared with landfill. The energy is achievable in the forms of heat and electricity; however, it has problems with efficiency when considering the high water content associated with Chinese FW. Hence, due to the low calorific value, it would require other additional materials such as fuel or papers, and plastics along with the FW to aid the process. Incineration also has some drawbacks in terms of emission of pollutants that are typical for fossil fuel combustion, such as

| Reference | 58,59 | 60 | 45,61 | 62 | 63 |
|-----------|------|-----|------|-----|-----|
| Country   | UK   | Korea | China | USA | Belgium |
| FW origin | Domestic FW | University restaurant | Domestic restaurant | Waste company | University restaurant |
| TS (%)²   | 23.74 ± 0.08 | 18.10 ± 0.60 | 16.63 | 30.90 ± 0.07 | 25.50 ± 0.40 |
| VS (%)²   | 21.71 ± 0.09 | 17.10 ± 0.60 | 14.90 | 26.35 ± 0.14 | 24.00 ± 0.60 |
| VS/TS (%) | 91.44 ± 0.39 | 94.00 ± 1.00 | 89.6 | 85.30 ± 0.65 | 93.46 |
| pH        | 4.71 ± 0.01 | 6.50 ± 0.20 | 5.40 | – | – |
| Water content | – | – | 80-90 | – | – |
| Carbohydrates (%)³ | 41.42 ± 1.55 | 61.70 | – | – | – |
| Proteins (%)³ | 15.10 ± 0.10 | 18.20 | – | – | – |
| Lipids (%)³ | 23.50 ± 0.30 | 12.87 | 1.5 | – | – |
| C (%)³     | 47.60 ± 0.50 | 46.67 | 48.20 | 46.78 ± 1.15 | – |
| N (%)³     | 3.44 ± 0.04 | 3.54 | 2.8 | 3.16 ± 0.22 | – |
| C/N        | 13.90 ± 0.20 | 13.20 ± 0.20 | 17.4 | 14.80 | – |
| Cellulose (%TS)³ | 4.61 ± 0.15 | – | – | – | – |
| Hemicellulose (%TS)³ | 3.48 ± 0.34 | – | – | – | – |
| Lignin-like (%TS)³ | 1.51 ± 0.02 | – | – | – | – |

²Wet basis.
³Dry basis.
⁴Calculated by Van Soest fractionation.
harmful (CO₂, CO, NOₓ, SO₂, dioxins, and dust). There is also considerable emission of highly harmful pollutants from the organic and inorganic matters such as heavy metals, polycyclic aromatic hydrocarbon, polychlorinated biphenyl, and polychlorinated dibenzodioxins. Fly ash and bottom ash from waste-burning plants are another form of dangerous pollutant considered as crucial problem, although there are now highly controlled incineration emission processes in newly designed incinerators.

### 2.2.3 Composting

Food waste, which is an organic waste, has a unique prospective for bioconversion as compost for fertilizers. Merits associated with compost are the benefit of using FW that might be landfilled to provide equilibrium of nutrients via low-cost fertilizer for agriculture. It also can sequester carbon, hence mitigating climate change. Irrespective of its numerous advantages, it has two main major constraints: the requirement for ample space for composting process and longtime operational procedure for the production of mature compost. Environmental challenges associated with the problem of VOC emission is another huge constraint.

### 2.2.4 Anaerobic digestion

Anaerobic digestion is a promising technology that recovers bioenergy from biomass or biosolid wastes. This technology is capable of converting biodegradable substrates into biogas (a mixture of about 60%-65% CH₄ and 35%-40% CO₂) through a community of anaerobic microorganisms. The nature of organic substrate characteristics in AD makes it possible for the categorization of the AD as wet (10% total solids), semi-dry (10%-20% TS), and dry (20% and above TS) bioconversion process. Although the wet AD and dry AD have unique advantages and shortcoming during the bioconversion of waste, the technology still faces some major challenges such as operational instability, quality of digestate that cannot be digested by microorganisms, or rather difficult/slowly digested substrates. The AD also faces the challenges of inhibitors that render inhibitory phenomenon in the reactor affecting microbial performance.

Therefore, the enhancement of operational conditions in the AD must be suitable for the microorganism to keep the process of bioconversion working correctly. Several critical parameters must be taken into consideration, most notably the role of the methanogenic microorganism since they have a low growth rate and sensitive to environmental factors. Other important parameters include pH, the temperature, substrate type and composition, and operational parameters such as organic loading rate, cultivation, and mixing.

In the treatment of waste with AD, different categories of reactors are applied. The generally used reactors include the batch system, the continuous first-stage, and the second-stage continuous bioreactors to improve bio-methanation. Specific example names of these reactors are the fixed-film bioreactor, anaerobic sequencing batch reactor (ASBR), up-flow anaerobic sludge blanket (UASB), continuously stirred tank reactor (CSTR), and also the tubular bioreactors. Meanwhile, the second most commonly adopted method in developing countries, China inclusive, is composting (with a rate ranging from 1% to 6%).

### 2.2.5 Foraging/animal feeding

Some developing countries propagated laws that promote using FW to feed animals; such countries have a high demand for animal feeding; an example is South Korea. Under such kinds of context, separation of FW from MSW has associated problems as collection and separation are not highly practiced. However, this was encouraged by law to feed animals, or use the FW as forage.

### 3 CHALLENGES FOR TREATMENT AND DISPOSAL OF RECALCITRANT ORGANIC RESIDUES DURING AD OF FOOD WASTE

Food waste valorization mostly occurred by the application of composting and AD process. The composting process occurred via biological degradation of organic matters in an aerobic environment, while that of the AD occurred via biological degradation of organic matters in an anaerobic environment. However, irrespective of associated benefits with AD of FW treatment, during screening and biological treatment of FW, there is a fraction of about 30% of the total FW materials remaining as ROR. These ROR constitute about 30% of the original FW that can be considered as resources with secondary values (Figure 1). The ROR schematic route was presented from the outcome of field investigations conducted on selected FW treatment facilities in China, and further studies conducted by Giwa et al. Summarily, solid residual matters generated from the AD process are plastics and high lignin matters incapable of undergoing complete degradation during biochemical treatment. Plastics and lignin and biomass materials posed a lot of treatment challenges; however, these materials have secondary value as resources and energy utilization.

Disposal consideration of ROR had postured a lot of treatment challenges. These residues eventually were mainly disposed of via landfill, open burning, and incineration routes; it leads to wasteful resource exploitation. The disposal routes, as mentioned earlier, create increasing pressures on waste management and consequent environmental impacts (eg, soil...
degradation, greenhouse gas (GHG) emissions, and water pollution). The frequency at which ROR are being generated needs receiving urgent attention for sustainable disposal techniques.

3.1 Factors influencing AD performance of food waste and recalcitrant organic residues

Anaerobic digestion is a promising technology that recovers bioenergy from biomass or biosolid wastes. This technology is capable of converting biodegradable substrates into biogas (a mixture of about 60%-65% CH₄ and 35%-40% CO₂) through a community of anaerobic microorganisms. Several critical parameters must be taken into consideration, most notably the role of the methanogenic microorganism since they have a low growth rate and sensitive to environmental factors. Other important parameters include pH, the temperature, substrate type, composition, and operating parameters such as organic loading rate, cultivation, and mixing.

Temperature is an important parameter that influences not only the activities of enzymes and coenzymes; it also has a tremendous effect on the quality of digestate (effluent) and biogas yield from AD. AD microorganisms can perform and grow in three different operating temperatures of psychrophilic (10-30°C), mesophilic (30-40°C), and thermophilic (50-60°C) conditions. Both thermophilic and mesophilic temperature conditions are widely applied in the operations of AD plants because methanogenic diversity and sensitivity to temperature are more pronounced. Anaerobic bacteria need different pH ranges for their growth, for example, a wide-ranging pH of 4.0-8.5 is required by fermentative bacteria, while a limiting range of 6.5-7.2 is favorable for methanogens' growth. Fermentative products that release free hydrogen ions into a solution through acidification of hydrocarbons, fatty acids, and proteins are the main mechanisms that affect the pH.

Usually, an increasing propionic acid concentration is the first sign of acidification that eventually leads to a fall in the pH value and a rise in CO₂ of the biogas contents. At the same time, there are natural buffering systems that can resist the pH change in AD reactors, and an example is the bicarbonate buffering system that prevents too strong acidification and too strong basification by the ammonia buffering system. One of the potential shortcomings of AD is its higher sensitivity toward toxicants. When an unfavorable alteration in the microbial population causes inhibitory for microbes, then the material can be considered to be inhibited or inhibition in the growth and metabolic activity. Although at considerable concentrations, some metals are required for active functions of enzymes and coenzymes in the AD process. An excessive quantity of such heavy metals might lead to inhibition of AD. Ammonia can be formed during the AD biodegradation process of protein or other nitrogen-rich organic substrates, and it mainly exists in the form of ammonium (NH₄⁺) and free ammonia (NH₃). Ammonia is also considered as an essential nutrient for the growth of AD microbes but can be an inhibitor when present at high concentrations. FW is a feedstock mostly treated in AD, and it has a lipid-rich resource with a lipid concentration of 5.0 g/L. During lipid degradation process, long-chain fatty acids (LCFA) are mainly composed of oleic acid (C18:1), linoleic acid (C18:2), and palmitoleic acid (C16:0) as the main intermediate by-products of lipid degradation process. LCFA can also be further converted to hydrogen and acetate by AD acetogenic bacteria through a β-oxidation process, and finally to methane via methanogenic archaea. VFA accumulation can exist from a high organic load, which can, therefore, influence pH in an AD; hence, their concentrations could be used as an indicator of reactor performance. AD phases are closely linked with each other, and therefore, if the first and second phases run too fast, the acid concentration rises because of fatty acid.
 accumulation resulting in pH value drops, and even failure of AD. It has been demonstrated that propionic acid to the acetic acid ratio that exceeds 1.4 g/L or acetic acid concentrations that exceed 0.8 g/L can lead to AD failure, and the propionic acid to acetic acid ratio could, therefore, be utilized as a measure of AD imbalance. The application of aromatic hydrocarbons at commercial and industrial scale continues to be on the rise with global concern. These aromatics can thus pose potential toxicity and recalcitrant to nature, plants, animals, and human. Meanwhile, of recent, interest in the application of AD processes to treat/reduce these aromatic compounds have been on the increase.

### 3.2 Principles of pyrolysis methods and advantages on recalcitrant organic residues

Pyrolysis, a thermal process with energy-efficient, environment-friendly, and economically sound, is considered an appropriate alternative for the treatment of RORs. Generally, pyrolysis is defined as the thermal decomposition of an organic matrix in a non-oxidizing atmosphere resulting in oil tar, solid char, and noncondensable gaseous products. Pyrolysis products can produce heat and power, both individually and simultaneously. Char obtained from pyrolysis of ROR has multiple applications, such as for soil improvement, carbon sequestration, and as an adsorbent precursor. The precise distribution of products depends mainly on many various pyrolysis factors such as heating rate, temperature, operating pressure, residence times of the vapors, and the converting biomass/residues and their states of mixing. As shown in Table 3, pyrolysis methods can be approached from three main points of view: slow/conventional or traditional, fast, and flash pyrolysis. It depends on the preferred name, however, be it slow, conventional, or the traditional, they are the same pyrolysis process. Slow pyrolysis takes several hours to complete and results in char yield as the main product at the temperature range of 400-600°C. However, different conditions can be applied for maximum yield of fuel gas and char in the presence of a catalyst, most notably at low temperature and low heating rate. This technique has been applied for centuries to produce methanol and yields approximately equal quantities of char, gas, and oil.

Fast pyrolysis or higher pyrolysis temperature referred to flash pyrolysis is a relatively new and promising technology. It involves a high oil yield achieved through rapid heating rates of 1 to >1000°C/s, with a short residence times of <2 seconds at temperatures of about 400-650°C, or higher if it was to be flash pyrolysis, or above 650°C, with rapid quenching of the vapors. Fast pyrolysis processes had gain prominence in the development for production of food flavors, specialty chemicals, and fuels (It is used to replace traditional slow pyrolysis processes which had much lower yields). These utilize short vapor residence times of between 30 and 1500 minutes and reactor temperatures around 500°C. Consideration for the application of both residence time and temperature control is essential to “freeze” the intermediates with moderate gas/vapor phase at temperatures of 400-500°C to maximize organic oil yields. Figueiredo et al. investigated the gas product property from lignin/bone structure pyrolysis at changing temperatures and heating rates.

Pyrolysis has the advantage of low capital investment and an oil final product that is transportable and can be converted via catalysis to fuels and valuable products such as food flavorings, fertilizers, resins, and other specialty chemicals that are fully compatible with existing petroleum infrastructure. This provides significant economic advantages over ethanol that requires parallel infrastructures for optimal operation. Besides, all pyrolysis products can be utilized in the pyrolysis system. Gas can be burned to help dry the incoming biomass and operate the reactor, while char and ash are promising soil amendments. Char can also be used as a fuel, and there is prospective to enlarge the resource base to comprise nontraditional feedstock such as lignin, sewage sludge, and even chicken litter.

### 3.2.1 Factors influencing pyrolysis performance of recalcitrant organic residues

The thermo-decomposition of RORs is dependent on various process parameters such as feedstock type, operating conditions, and physicochemical properties of waste. These conditions ultimately affect the waste conversion time or pyrolysis rate with product distribution and quality based on objectives of the pyrolysis products desired. Pyrolysis is most convenient for waste with low moisture contents rather than highly wet FW. Different studies performed at both laboratory scale and pilot scale also determined components of MSWs and pyrolysis behavior of different waste.
materials such as cloths, plastics fibers, biomass, and plastic materials.\textsuperscript{21,26,120,121} Different interaction synergy and operational parameters influencing pyrolysis among waste components were also investigated.\textsuperscript{122} The decomposition of the waste residues is much favored through fast heating rates with yields of more gases and less production of char. Oil/tar production is enhanced at fast heating rates of recalcitrant residues due to a decrease in mass and heat transfer limitations resulting in available short time for the secondary reaction.\textsuperscript{18,104,123} Liden et al.\textsuperscript{124} reported there is a significant effect of the vapor residence time on product yields in the fluidized bed reactor. Abnisa et al.\textsuperscript{125} reported extensively on review studies by different authors on the co-pyrolysis of mixed biomass plastics under different pyrolysis conditions.

\section*{4 | PYROLYSIS COUPLED AD CONSIDERATIONS}

Pyrolysis represents an alternative process to improve the energy and economic value of ROR utilization with the ability to provide three end products: a gas, oil, and a solid residue (char) which all have the potential to be further recycled. Pyrolysis techniques have long been in existing, but its utilization is still at the infant stage. However, recently, this technique is receiving attention globally from researchers to valorize different types of waste materials and obtain valuable products (Table 4).\textsuperscript{18,32} So far, compared to the individual process, the integrated processes could offer significant advantages in recovering bioenergy from ROR, reducing digestate management cost, recycling, and reutilizing digestate, and lowering greenhouse gas discharge. Feng and Lin\textsuperscript{41} proposed pyrolysis and AD coupling arrangement can be categorized into three (AD and pyrolysis; pyrolysis and AD; and AD-pyrolysis-AD). In the technology combination and operation, consideration on the nature of waste to be treated, and final goals are paramount to avert technical shortcomings and harness the coupling strength.

\subsection*{4.1 | Utilization of pyrolysis products in anaerobic digestion}

Research gap in the practical application of pyrolysis by-products in bioprocess technology was identified; hence, further utilization via pyrolysis coupled AD is being proposed.\textsuperscript{18,41} The proposed route is a new research direction presently receiving global attention. Most researchers only investigated the application of simulated pyrolysis syngas in AD.\textsuperscript{126,127} However, studies are rarely available on the use of the “real pyrolysis syngas” in AD. Similarly, several literatures on char studies reported only short time run operation results of char in AD.\textsuperscript{40,128,129} Integration of AD and pyrolysis offers further potentially synergistic combinations which include use of digestate as feedstock for pyrolysis,\textsuperscript{44,101} syngas bio-methanation,\textsuperscript{18,130} or use of chars as an additive in AD to overcome inhibition problems.\textsuperscript{11,131-133} Besides, for instance, the digestate from AD could be a suitable feedstock for pyrolysis to enhance biochar production.\textsuperscript{5,131} while the remaining char in the digestate could serve as a soil conditioner if the digestate is utilized as composted.\textsuperscript{11,43,134}

\subsection*{4.1.1 | Pyrolysis oil effects in anaerobic digestion}

One group of the pyrolysis by-products with no direct use besides burning is the condensable fraction of the pyrolysis gas that is referred to as pyrolysis oils/tars.\textsuperscript{135,136} It is a dark brown flowing fluid with a typical stink that comprises of a complex mixture of about 400 organic compounds.\textsuperscript{104,137} This main dark brown product, oil, can also be described as a miscible mixture of polar organics about 75-80 wt\% and water about 20-25 wt\%.\textsuperscript{107} It is generally known to be a potential feedstock for the production of energy, biofuels, and chemicals. Nevertheless, with consideration to the oil/tar extensive varieties of complex components and its apparent toxicity, thermal or catalytic upgrading techniques are necessary to meet the high requirements for fuel and chemical production.\textsuperscript{138,139} Mostly, mentioned treatment methods for oil/tar in the literature focused on solvent separation process to obtain fractions with similar polarities and to concentrate the un-distillable fraction.\textsuperscript{138}

\subsection*{4.1.2 | Pyrolysis syngas in anaerobic digestion}

Pyrolysis syngas contains hydrogen as one of the major components and could biologically be converted to methane through AD of microbial activities rather than via catalytic chemical process.\textsuperscript{18,41,126,140} The fermentation process offers several benefits over the chemical catalytic process, such as a more specific process, higher yields, lower energy consumption, being environmentally friendly, and having better robustness.\textsuperscript{141,142} It should be noted that the hydrogenotrophic methanogens can be increased to promote hydrogen consumption, thereby generating more methane.\textsuperscript{143} The application of pyrolysis to treat and recycle ROR to generate real syngas and the subsequent utilization of the real syngas for bio-methanation during AD treatment of FW was also explored by Giwa et al.\textsuperscript{18} In their studies, the second-stage pyrolysis of recalcitrant generates syngas with a high H\textsubscript{2}-to-CO ratio (60:20 vol\%) that produced almost 100\% more methane than the control during the bio-methanation process. However, a high level of CO\textsubscript{2} in the biogas during purification for improved bio-methanation can be a disadvantage when combined with low H\textsubscript{2} concentration in the syngas.\textsuperscript{144}
| Items | Types of waste                        | Types of coupling technology process | Remarks                                                                                                                                                                                                 | Authors |
|-------|-------------------------------------|-------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
| 1     | Lignocellulose biomass              | AD-pyrolysis                        | The study reported that AD-pyrolysis can improve the electricity benefit with about 42% when compared with the stand-alone AD process. Pyrolysis-AD integration is still scare; meanwhile, studies on pyrolysis toxicants to AD need to be further investigated. AD-pyrolysis-AD is a suitable technique for the degradation of biomass and subsequent utilization of the digestate and residues accordingly. | 41      |
| 2     | Paper mill sludge                   | AD combined pyrolysis               | The combined process had improved self-sufficient of the energy for the treatment process.                                                                                                                                                                         | 122     |
| 3     | Nonbiodegradable green waste        | Pyrolysis combined AD               | It enhanced bio-methanation, while the excess amount of energy can be used to fulfill the demanded heat of the processes when combined.                                                                                                                            | 39      |
| 4     | Aqueous liquor from biomass digestes | Pyrolysis integrated with AD        | The study reported the pyrolysis aqueous liquors acquired from the digestate pyrolysis can be treated in AD with COD removal rates of 63% and an enhanced methane yield was achievable.                                                                 | 131     |
| 5     | Animal slurries, manure, and energy crops (solid digestates) | Integration of AD and pyrolysis | This integrated route had shown advantages such as generation of different bioenergy carriers such as biogas, bio-methane from AD, and bio-oil, and syngas from pyrolysis is feasible. In addition, it can reduce GHG and improve agriculture productivity. | 42      |
| 6     | AD of pyrolytic C1-C4 of biomass    | Integrating pyrolysis and AD        | Pyrolytic C1-C4 is considered undesirable for bio-oil properties creating problems such as acidity and low thermal conductivity. Therefore, appropriate utilization route will be to convert the C1-C4 into methane via AD.                                      | 148     |
| 7     | Food waste                          | Combining AD and pyrolysis          | This study elucidated on the assessment of FW treatment via AD-pyrolysis and respective transformation to gas, oil, and solid yields for energy production. The limitations and possibilities of lignin biomass disintegration, reduction, and conversion to energy were addressed. Based on this combined process, high concentration of nutrient materials suitable as soil condition and agronomy can be accomplished. | 44      |
| 8     | Sewage sludge                       | AD integrated with pyrolysis        | Coupling pyrolysis and AD will offer pathways to improve the recovery of energy from sewage sludge. The adoption of AD should firstly be employed afterward; pyrolysis combination pathway will offer option for sludge with high organic content due to sludge great transformation rate to energy. | 149     |
| 9     | Different waste streams             | AD to gasification pyrolysis and hydro-thermal process | The authors discussed individual technology established on the treatment with thermal process coupled to AD process: AD-Py, AD-Gs, and AD-HTC. Future research was proposed to evaluate the most favorable integration route. | 24      |
| 10    | Difficult degradable waste from MSW (lignocellulose materials) | Pyrolysis-AD, pyrolysis combined with CHP. | Pyrolysis of difficult biodegradable leftover to generate syngas, biochar, and bio-oil was considered. The comparative technology performance between pyrolysis-CHP and pyrolysis-AD showed efficiency (79.9% and 67%), respectively. | 150     |
| 11    | Recalcitrant organic residues (ROR) | Two-stage pyrolysis coupled AD      | The second-stage pyrolysis of ROR produced syngas with a high H₂-to-CO ratio (60:20 vol%) that generated about 100% more CH₄ compared with the control during bio-methanation. Higher H₂ concentration expedites the CO degradation rate, with a high CO content; the degradation rate of H₂ is decreased. Coupling second-stage pyrolysis with the AD process averts the challenges of conventional ROR treatments. It would produce beneficial products such as H₂-rich syngas and enhanced bio-methanation in the AD treatment of FW. | 18      |
4.1.3 | Pyrolysis of char in anaerobic digestion

Char can be referred to be pyrogenic carbon-rich materials generated from carbon-neutral sources. Besides, Lehmann et al\textsuperscript{73} reported that biochar could also be carbon-negative, that is, it can be used as a carbon sink, which captures from the atmosphere carbon that will not be released back to the atmosphere. Biochar has a series of applications such as fuel, for some metallurgical processes, as an attractive substitute for coke derived from fossil fuels, since it contains low concentrations of metals. Char is also an excellent fertilizer: It improves soil texture as a soil conditioner,\textsuperscript{43} and it retains and slowly releases nutrients and water while acting as upkeep for beneficial organisms.\textsuperscript{73,145,146} Giwa et al\textsuperscript{11} in their research, employed the utilization of biochar in the AD of FW treatment over long-run operations to enhance reactor performance at high organic loading rate and biogas improvement.

Although ROR pyrolysis signifies only a little portion of energy production globally, it has the potential to generate energy at a lower cost than other energy systems and most especially when integrated with the AD process.\textsuperscript{18,41} With its carbon-negative footprint, pyrolysis of biomass/ROR can do this in a way that it can contribute to a reduction in greenhouse gas emissions.\textsuperscript{73} Soil organic carbon is one of the largest reservoirs as an interface with the atmosphere and also enhancing natural processes thought to be the most cost-effective means of reducing atmospheric CO\textsubscript{2}.\textsuperscript{147} Most of this research is focused on improving material properties of the chars' quality for agricultural purposes, on enhancing the recovery of potential resources from difficult degradable feedstocks for energetic and economic efficiency, and also on minimizing the production and release of undesirable by-products.\textsuperscript{147}

4.2 | Future outlook

The primary appropriateness of an AD treatment has been previously reported for bio-oil obtained from pyrolysis of wood,\textsuperscript{151} cornstalk pyrolysis to get aqueous phase,\textsuperscript{40} and pyrolysis of timber with the flash method for the production of oil.\textsuperscript{152} Liquors from coal gasification have constituents that are vulnerable to AD process\textsuperscript{153} and oil from maize silage hydrothermal carbonization.\textsuperscript{154} Deployment of AD for the treatment of this oil was identified to have reduced huge portions of the organic portions, together with phenol considered as hazardous compounds.\textsuperscript{131}

Meanwhile, inhibition of the AD microbes' optimal performance might occur via the treatment of oils/tars directly from ROR second-stage pyrolysis. However, the syngas with high hydrogen content from second-stage pyrolysis of recalcitrant residues is feasible for bio-methanation in AD of FW by the mesophilic bacteria.\textsuperscript{18,23,143} The application of mesophilic bacteria which uses acetyl-CoA pathway was investigated by Henstra et al.\textsuperscript{155} It describes the process routes by which bacteria use syngas for the production of ethanol. During the conversion process, CO and hydrogen are oxidized, while CO\textsubscript{2} is lessening several periods till the methylytetrahydrofolate is shaped. The linked methyl group formed with the CO created via the CO\textsubscript{2} reduction and CoA remaining in the cell are further transformed to acetyl-CoA via acetyl-CoA synthase and CO dehydrogenase. Finally, different types of valuable compounds and ethanol are obtainable from acetyl-CoA.\textsuperscript{156,157} The syngas has different routes of application: an energy source via taking advantages of the CH\textsubscript{4} and CO etc, as biogas and biodiesel for transport, valuable chemicals such as NH\textsubscript{4} and CH\textsubscript{2}OH; and the usage as electric energy and gas fuel to fire thermal plants.\textsuperscript{158,159} Different ratio of the pyro-gases indicates a potential use of them for cooking or for process heating.\textsuperscript{160} The biological process often adopted in biomass and ROR treatment offers biogas with high CO\textsubscript{2} content, thereby reducing its energy value. In other work,\textsuperscript{160} the consumption of hydrogen as a source was reported to improve biogas in their anaerobic digester (90%-100%) indicating that the reaction was conducted efficiently in the reactor.\textsuperscript{18,160}

The AD system itself is faced with various challenges that range from inhibition and quality of digestates produced.\textsuperscript{11,78} The application of pyrolysis by-products such as biochar can assist in keeping AD robust and mitigating inhibition.\textsuperscript{11,161} Though this technology combined is still at its prime, but receiving worldwide research attention. Hence, it seems evident that in-depth investigations using a more dependable and systematic approach with the existing reports in the literature are still needed. This process will further assist in quantifying the level of sustainability as related to technical issues, environmental, energy, and economic feasibility of the coupling of pyro-AD.

5 | CONCLUSIONS

Food waste production and associated ROR are increasing worldwide. The traditional methods of these wastes disposal are no longer feasible as regards economic and environmental perspectives. The pyrolysis and AD were reviewed in this paper and proposed considerations for simultaneous treatment of FW and ROR with the purpose to improve the bioenergy and the possibility of pyrolysis by-product recycling in AD. In the fundamental review of each technology, it was apparent each had some challenges. Nevertheless, the selection of the best strategy for the treatment and sustainable utilization of FW and ROR has been considered to overcome these bottlenecks. In this review, both simultaneously play a complementary role to one another when coupled together. The second-stage pyrolytic treatment route will provide an option
for utilization of inherent bioenergy potential in oil/tar/vapor for high hydrogen syngas that can eventually utilize further in AD for bio-methanation. Oil toxicity on microbes when directly used in the anaerobic digester will be wholly averted. Biochar effect to mitigating microbial stress, increase methane contents, digestate quality, and soil amendment has been previously elucidated and still receiving global attention.

ACKNOWLEDGMENTS

This work was supported by the Major Science and Technology Program for Water Pollution Control and Treatment of China (Grant No. 2017ZX07102-004) and the National Key Technology Support Program of China (Grant No. 2014BAC27B01). Additional support via Lab 913, Tsinghua University, School of Environment, and the Waste Water Pollution Control (Grant No. 01160056) of the Green Intelligent Environmental School, Yangtze Normal University, China, are highly acknowledged.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ORCID

Abdulmoseen Segun Giwa https://orcid.org/0000-0001-9905-0312

REFERENCES

1. Gao A, Tian Z, Wang Z, Wennersten R, Sun Q. Comparison between the technologies for food waste treatment. Energy Procedia. 2017;105:3915-3921.
2. Oladepo OW, Ilori MO, Taiwo KA. Assessment of the Waste Generation and Management Practices in Nigerian Food Industry: Towards a Policy for Sustainable Approaches. Am J Sci Ind Res. 2015;6:12-22.
3. FAO. Food Wastage Footprint. Impacts on Natural Resources. Summary Report; 2013.
4. Mirmohamadsadeghi S, Karimi K, Tabatabaei M, Aghbashlo M. Biogas Production from Food Wastes: A Review on Recent Developments and Future Perspectives. Bioresour Technol Rep. 2019;7:100202.
5. Opatokun SA, Kan T, Al Shoabi A, Srinivasakannan C, Strezov V. Characterization of food waste and its digestate as feedstock for thermochemical processing. Energy Fuels. 2016;30:1589-1597.
6. Capson-Tojo G, Rouez M, Crest M, Steyer JP, Delgenés JP, Escudíe R. Food waste valorization via anaerobic processes: a review. Rev Environ Sci Biotechnol. 2016;15:499-547.
7. Melikoglu M, Lin C, Webb C. Analysing global food waste problem: pinpointing the facts and estimating the energy content. Cent Eur J Eng. 2013;3:157-164.
8. European Commission T. Report, Preparatory Study on Food Waste Across Eu 27; 2010.
9. Zhou H, Meng A, Long Y, Li Q, Zhang Y. An overview of characteristics of municipal solid waste fuel in China: physical, chemical composition and heating value. Renew Sustain Energy Rev. 2014;36:107-122.
10. Jang P. The Status Quo and Development Trend Analysis of Restaurant Kitchen Waste Disposal Industry in 2018; 2018.
11. Giwa AS, Heng X, Chang F, et al. Effect of biochar on reactor performance and methane generation during the anaerobic digestion of food waste treatment at long-run operations. J Environ Chem Eng. 2019;7:103067.
12. Li L, Peng X, Wang X, Wu D. Anaerobic digestion of food waste: a review focusing on process stability. Bioresour Technol. 2018;248:20-28.
13. Ahamed A, Yin K, Ng B, Ren F, Chang VW-C, Wang J-Y. Lifecycle assessment of the present and proposed food waste management technologies from environmental and economic impact perspectives. J Clean Prod. 2016;131:607-614.
14. Thi N, Kumar G, Lin C-Y. An overview of food waste management in developing countries: current status and future perspective. J Environ Manage. 2015;157:220-229.
15. Thyberg KL, Tonjes DJ. The environmental impacts of alternative food waste treatment technologies in the U.S. J Clean Prod. 2017;158:101-108.
16. McKinsey Global Institute. Resource Revolution: Meeting the World’s Energy, Materials, Food, and Water Needs. McKinsey; 2011:224. https://www.mckinsey.com~/media/McKinsey/Business%20Functions/Sustainability/Our%20Insights/Resource%20revolution/MGI_Resources_revolution_executive_summary.ashx
17. Giwa AS, Xu H, Wu J, et al. Sustainable recycling of residues from the food waste (FW) composting plant via pyrolysis: thermal characterization and kinetic studies. J Clean Prod. 2018;180:43-49.
18. Giwa AS, Chang F, Xu H, et al. Pyrolysis of difficult biodegradable fractions and the real syngas bio-methanation performance. J Clean Prod. 2019;233:711-719.
19. Kung C-C, Kong F, Choi Y. Pyrolysis and biochar potential using crop residues and agricultural wastes in China. Ecol Indic. 2015;51:139-145.
20. McKendry P. Energy production from biomass (part 1): overview of biomass. Bioresour Technol. 2002;83:37-46.
21. Chang F-M, Wang Q-B, Segun G, Jia J-W, Wang K-J. Two-stage catalytic pyrolysis of sewage sludge for syngas production. Zhongguo Huangjing Kexue/China Environ Sci. 2013;35:804-810.
22. Chen D, Yin L, Wang H, He P. Reprint of: Pyrolysis technologies for municipal solid waste: a review. Waste Manag. 2015;37:116-136.
23. Patinvoth RJ, Osadolor OA, Chandollas K, Sáravái Horváth I, Taherzadeh MJ. Innovative pretreatment strategies for biogas production. Bioresour Technol. 2017;224:13-24.
24. Pecchi M, Baratieri M. Coupling anaerobic digestion with gasification, pyrolysis or hydrothermal carbonization: a review. Renew Sustain Energy Rev. 2019;105:462-475.
25. Oyedun AO, Gebreegziabher T, Ng D, Hui CW. Mixed-waste pyrolysis of biomass and plastics waste – a modelling approach to reduce energy usage. Energy. 2014;75:127-135.
26. Çepelioğullar Ö, Pütün AE. Thermal and kinetic behaviors of biowaste and plastic wastes in co-pyrolysis. Renew Sustain Energy Rev. 2014;75:127-135.
27. Huang Y-F, Chiueh P-T, Lo S-L. A review on microwave pyrolysis of lignocellulosic biomass. Sustain Environ Res. 2016;26:103-109.
28. Budarin VL, Clark JH, Lanigan BA, et al. The preparation of high-grade bio-oils through the controlled, low-temperature microwave activation of wheat straw. Bioresour Technol. 2009;100:6064-6068.

29. Sajdak M, Muzyka R, Habak J, Slowik K. Use of plastic waste as a fuel in the co-pyrolysis of biomass. Part III: optimisation of the co-pyrolysis process. J Anal Appl Pyrolysis. 2015;112:298-305.

30. Ward J, Rasul MG, Bhiyai M. Energy recovery from biomass by fast pyrolysis. Procedia Eng. 2014;90:669-674.

31. Serio MA, Cosgrove JE, Wójcikwicz MA. Methane production from pyrolysis of mixed solid wastes. In: 42nd International Conf Environ Syst; 2012:1-14.

32. Luo S, Xiao B, Hu Z, Liu S. Effect of particle size on pyrolysis of single-component municipal solid waste in fixed bed reactor. Int J Hydrogen Energy. 2010;35:93-97.

33. Sharypov VI, Marin N, Beregovtsova NG, et al. Co-pyrolysis of wood biomass and synthetic polymer mixtures. Part I: influence of experimental conditions on the evolution of solids, liquids and gases. J Anal Appl Pyrolysis. 2002;64:15-28.

34. Chattopadhyay J, Pathak TS, Srivastava R, Singh AC. Catalytic co-pyrolysis of paper biomass and plastic mixtures (HDPE (high density polyethylene), PP (polypropylene) and PET (polyethylene terephthalate)) and product analysis. Energy. 2016;103:513-521.

35. Saad JM, Williams PT. Catalytic dry reforming of waste plastics from different waste treatment plants for production of synthesis gases. Waste Manag. 2016;58:214-220.

36. Alhassan M, Andresen J. Effect of bone during fixed bed pyrolysis of pistachio nut shell. Int J Sci Eng Investig. 2013:2:37-48.

37. Berruti FM, Ferrante L, Briens C, Berruti F. Meat and Bone Meal Pyrolysis Study in a Laboratory-Scale Bubbling Fluidized Bed Reactor; 2013:1-22.

38. Cai J, He P, Wang Y, Shao L, Lu F. Effects and optimization of the use of biochar in anaerobic digestion of food wastes. Waste Manag Res. 2016;34:409-416.

39. Salman CA, Schwede S, Thorin E, Yan J. Enhancing biomethane production by integrating pyrolysis and anaerobic digestion processes. Appl Energy. 2017;204:1074-1083.

40. Torri C, Fabbrini D. Biochar enables anaerobic digestion of aqueous phase from intermediate pyrolysis of biomass. Bioresour Technol. 2014;172:335-341.

41. Feng Q, Lin Y. Integrated processes of anaerobic digestion and pyrolysis for higher bioenergy recovery from lignocellulosic biomass: a brief review. Renew Sustain Energy Rev. 2017;77:1272-1287.

42. Monlau F, Francavilla M, Sambusiti C, et al. Toward a functional integration of anaerobic digestion and pyrolysis for a sustainable resource management. Comparison between solid-digestate and its derived pyrochar as soil amendment. Appl Energy. 2016;169:652-662.

43. Opatokun SA, Yousef LF, Strezov V. Agronomic assessment of pyrolysed food waste digestate for sandy soil management. J Environ Manage. 2017;187:24-30.

44. Opatokun SA, Strezov V, Kan T. Product based evaluation of pyrolysis of food waste and its digestate. Energy. 2015;92:349-354.

45. Wen Z, Wang Y, De Clercq D. What is the true value of food waste? A case study of technology integration in urban food waste treatment in Suzhou City, China. J Clean Prod. 2016;118:88-96.

46. Zhang C, Su H, Baeyens J, Tan T. Reviewing the anaerobic digestion of food waste for biogas production. Renew Sustain Energy Rev. 2014;38:383-392.

47. Ngoc T, Dung B, Sen B, Chen C. Food waste to bioenergy via anaerobic processes. Energy Procedia. 2014;61:307-312.

48. Phuong T, Pham T, Kaushik R, Parshetti GK, Mahmood R, Balasubramanian R. Food waste-to-energy conversion technologies: current status and future directions. Waste Manag. 2015;38:399-408.

49. COM(2011). 112 Final, A Roadmap for Moving to a Competitive Low Carbon Economy in 2050. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions; 2012.

50. Scarlat N, Dallemel JF, Fuhl F. Biogas: developments and perspectives in Europe. Renew Energy. 2018;129:457-472.

51. Directive 2015/1513. Directive (EU) 2015/1513 of the European Parliament and of the Council Amending Directive 98/70/EC Relating to the Quality of Petrol and Diesel Fuels and Amending Directive 2009/28/EC on the Promotion of the Use of Energy from Renewable Sources; 2015.

52. Scarlat V, Dallemel J-F, Monforti-Ferrario F, Banja M. Renewable energy policy framework and bioenergy contribution in the European union: an overview from national renewable energy action plans and progress reports. Renew Sustain Energy Rev. 2015;51:969-985.

53. Statista. Amount of Disposed Garbage in China from 1990 to 2017 (in million tons). https://www.statista.com/statistics/279117/amount-of-disposed-garbage-in-china. (n.d.).

54. Zhao X, Li L, Wu D, Xiao T, Ma Y, Peng X. Modified Anaerobic Digestion Model No. 1 for modeling methane production from food waste in batch and semi-continuous anaerobic digestions. Bioresour Technol. 2019;271:109-117.

55. De Clercq D, Wen Z, Fan F, Caicedo L. Biomethane production potential from restaurant food waste in megacities and project level-bottlenecks: a case study in Beijing. Renew Sustain Energy Rev. 2016;59:1676-1685.

56. Pham T, Kaushik R, Parshetti GK, Mahmood R, Balasubramanian R. Food waste-to-energy conversion technologies: current status and future directions. Waste Manag. 2015;38:399-408.

57. Liu G. Food Losses and Food Waste in China: A First Estimate. OECD Food, Agric Fish Pap; 2014:1-29.

58. Banks CJ, Zhang Y, Jiang Y, Heaven S. Trace element requirements for stable food waste digestion at elevated ammonia concentrations. Bioresour Technol. 2012;104:127-135.

59. Zhang L, Jahng D. Long-term anaerobic digestion of food waste stabilized by trace elements. Waste Manag. 2012;32:1509-1515.

60. Zhang L, Lee Y-W, Jahng D. Anaerobic co-digestion of food waste and piggery wastewater: focusing on the role of trace elements. Bioresour Technol. 2011;102:5048-5059.

61. Liu X, Gao X, Wang W, Zheng L, Zhou Y, Sun Y. Pilot-scale anaerobic co-digestion of municipal biomass waste: Focusing on biogas production and GHG reduction. Renew Energy. 2012;44:463-468.

62. Zhang R, El-Mashad HM, Hartman K, et al. Characterization of food waste as feedstock for anaerobic digestion. Bioresour Technol. 2007;98:929-935.

63. De Vrieze J, De Lathouwer L, Verstraete W, Boon N. High-rate iron-rich activated sludge as stabilizing agent for the anaerobic digestion of kitchen waste. Water Res. 2013;47:3732-3741.

64. Bernstad A, la Cour Jansen J. Review of comparative LCAs of food waste management systems – current status and potential improvements. Waste Manag. 2012;32:2439-2455.
56. Zhang Y, Arnold R, Paavola T, Vaz F. Compositional analysis of food waste entering the source segregation stream in four European regions and implications for valorisation via anaerobic digestion. In: Fourteenth Int Waste Manag Landfill. Symp; 2013. http://eprints.soton.ac.uk/359726/. 
57. Zhang DQ, Tan SK, Gersberg RM. Municipal solid waste management in China: status, problems and challenges. J Environ Manage. 2010;91:1623-1633. 
58. Mouli JA, Allan SR, Hewitt CN, Berners-Lee M. Greenhouse gas emissions of food waste disposal options for UK retailers. Food Policy. 2018;77:50-58. 
59. Yang N, Zhang H, Chen M, Shao L-M, He P-J. Greenhouse gas emissions from MSW incineration in China: impacts of waste characteristics and energy recovery. Waste Manag. 2012;32:2552-2560. 
60. Girotto F, Alibardi L, Cossu R. Food waste generation and industrial uses: a review. Waste Manag. 2015;45:32-41. 
61. Mukherjee A, Debnath B, Ghosh SK. A review on technologies of removal of dioxins and furans from incinerator flue gas. Procedia Environ Sci. 2016;35:528-540. 
62. Youcai Z, Youcai Z. Municipal solid waste incineration process and generation of bottom ash and fly ash. In: Pollut Control Resour Recover Munic Solid Wastes Inciner; 2017:1-59. 
63. de Araújo A, de Melo WJ, Singh RP. Municipal solid waste compost amendment in agricultural soil: changes in soil microbial biomass. Rev Environ Sci Biotechnol. 2010;9:41-49. 
64. Beach RH, Creason J, Ohrel SB, et al. Global Mitigation Potential and Costs of Reducing Agricultural Non-CO2 Greenhouse Gas Emissions Through 2050, 2016. 
65. Wei Y, Li J, Shi D, Liu G, Zhao Y, Shimaoa T. Environmental challenges impeding the composting of biodegradable municipal solid waste: a critical review. Resour Conserv Recycl. 2017;122:51-65. 
66. Hartmann H, Ahring BK. Strategies for the anaerobic digestion of the organic fraction of municipal solid waste: an overview. Water Sci Technol. 2006;53:7-22. 
67. Colazo A-B, Sánchez A, Font X, Colón J. Environmental impact of rejected materials generated in organic fraction of municipal solid waste anaerobic digestion plants: comparison of wet and dry process layout. Waste Manag, 2015;43:84-97. 
68. Fagbohungbe MO, Herbert B, Hurst L, et al. The challenges of anaerobic digestion and the role of biochar in optimizing anaerobic digestion. Waste Manag. 2017;61:236-249. 
69. Holm-Nielsen JB, Al Seadi T, Oleskowicz-Popiel P. The future of anaerobic digestion and biogas utilization. Bioresour Technol. 2009;100:5478-5484. 
70. Appels L, Lauwers J, Degrève J, et al. Anaerobic digestion in global bio-energy production: potential and research challenges. Renew Sustain Energy Rev. 2011;15:4295-4301. 
71. Jha P, Schmidt S. Reappraisal of chemical interference in anaerobic digestion processes. Renew Sustain Energy Rev. 2017;75:954-971. 
72. Chen Y, Cheng JJ, Creamer KS. Inhibition of anaerobic digestion process: a review. Bioresour Technol. 2008;99:4044-4064. 
73. Weiland P. Biogas production: current state and perspectives. Appl Microbiol Biotechnol. 2010;85:849-860. 
74. Beach RH, Creason J, Ohrel SB, et al. Biochar sequestration in terrestrial ecosystems – a review. Rev Environ Sci Biotechnol. 2010;9:41-49. 
75. de Araújo A, de Melo WJ, Singh RP. Municipal solid waste compost amendment in agricultural soil: changes in soil microbial biomass. Rev Environ Sci Biotechnol. 2010;9:41-49. 
76. Beach RH, Creason J, Ohrel SB, et al. Global Mitigation Potential and Costs of Reducing Agricultural Non-CO2 Greenhouse Gas Emissions Through 2050, 2016. 
77. Youcai Z, Youcai Z. Municipal solid waste incineration process and generation of bottom ash and fly ash. In: Pollut Control Resour Recover Munic Solid Wastes Inciner; 2017:1-59. 
78. de Araújo A, de Melo WJ, Singh RP. Municipal solid waste compost amendment in agricultural soil: changes in soil microbial biomass. Rev Environ Sci Biotechnol. 2010;9:41-49. 
79. Youcai Z, Youcai Z. Municipal solid waste incineration process and generation of bottom ash and fly ash. In: Pollut Control Resour Recover Munic Solid Wastes Inciner; 2017:1-59. 
80. Mukherjee A, Debnath B, Ghosh SK. A review on technologies of removal of dioxins and furans from incinerator flue gas. Procedia Environ Sci. 2016;35:528-540. 
81. Youcai Z, Youcai Z. Municipal solid waste incineration process and generation of bottom ash and fly ash. In: Pollut Control Resour Recover Munic Solid Wastes Inciner; 2017:1-59. 
82. de Araújo A, de Melo WJ, Singh RP. Municipal solid waste compost amendment in agricultural soil: changes in soil microbial biomass. Rev Environ Sci Biotechnol. 2010;9:41-49. 
83. Beach RH, Creason J, Ohrel SB, et al. Global Mitigation Potential and Costs of Reducing Agricultural Non-CO2 Greenhouse Gas Emissions Through 2050, 2016. 
84. Roopnarain A, Adeleke R. Current status, hurdles and future prospects of biogas digestion technology in Africa. Renew Sustain Energy Rev. 2017;67:1162-1179. 
85. Bouallagui H, Touhami Y, Ben Cheikh R, Hamdi M. Bioreactor performance in anaerobic digestion of fruit and vegetable wastes. Process Biochem. 2005;40:989-995. 
86. Arunabat J, Panico A, Esposito G, Pirozzi F, Lens P. Pretreatment methods to enhance anaerobic digestion of organic solid waste. Appl Energy. 2014;123:143-156. 
87. Tai J, Zhang W, Che Y, Feng D. Municipal solid waste source-separated collection in China: a comparative analysis. Waste Manag. 2011;31:1673-1682. 
88. Ephraim A, Pham Minh D, Lebonnois D, Peregrina C, Sharrock P, Nizhou A. Co- pyrolysis of wood and plastics: Influence of plastic type and content on product yield, gas composition and quality. Fuel. 2018;231:110-117. 
89. Tang Z, Chen W, Chen Y, Yang H, Chen H. Co- pyrolysis of microalgae and plastic: characteristics and interaction effects. Bioresour Technol. 2019;274:145-152. 
90. Deublein D, Steinhauser A. Biogas from Waste and Renewable Resources: An Introduction. 2nd ed.; 2010. 
91. Wang H, Zhang Y, Angelidaki I. Ammonia inhibition on hydrogen enriched anaerobic digestion of manure under mesophilic and thermophilic conditions. Water Res. 2016;105:314-319. 
92. Gupta P, Ray J, Aggarwal BK, Goyal P. Food processing residue analysis and its functional components as related to human health: recent developments. Austin J Nutr Food Sci. 2015;3:1-7. 
93. Nielsen HB, Angelidaki I. Strategies for optimizing recovery of the biogas process following ammonia inhibition. Bioresour Technol. 2008;99:7995-8001. 
94. Lü F, Luo C, Shao L, He P. Biochar alleviates combined stress of ammonium and acids by firstly enriching Methanosetae and then Methanosarcina. Water Res. 2016;90:34-43. 
95. Huishoff Pol LW, De Castro Lopes SI, Lettinga G, Lens P. Anaerobic sludge granulation. Water Res. 2004;38:1376-1389. 
96. Sousa DZ, Salvador AF, Ramos J, et al. Activity and viability of methanogens in anaerobic digestion of unsaturated and saturated long-chain fatty acids. Appl Environ Microbiol. 2013;79:4239-4245. 
97. Gasser A, Neczaj E, Singh BR, Almás R, Brattebø H, Kacprzak M. Anaerobic digestion of sewage sludge with grease trap sludge and municipal solid waste as co-substrates. Environ Res. 2017;155:249-260. 
98. Martín-González L, Colturato LF, Font X, Vicent T. Anaerobic co-digestion of the organic fraction of municipal solid waste with FOG waste from a sewage treatment plant: recovering a wasted methane potential and enhancing the biogas yield. Waste Manag. 2010;30:1854-1859. 
99. Kaparaju P, Buendia I, Ellegaard L, Angelidakia I. Effects of mixing on methane production during thermophilic anaerobic digestion of manure: lab-scale and pilot-scale studies. Bioresour Technol. 2008;99:4919-4928. 
100. Wang H, Zhu S, Qu B, Zhang Y, Fan B. Anaerobic treatment of source-separated domestic bio-wastes with an improved upflow solid reactor at a short HRT. J Environ Sci. 2017;66:255-264. 
101. Inyang M, Gao B, Pullmanappalli P, Ding W, Zimmerman AR. Biochar from anaerobically digested sugarcane bagasse. Bioresour Technol. 2010;101:8868-8872.
102. Ahring BK, Sandberg M, Angelidaki I. Volatile fatty acids as indicators of process imbalance in anaerobic digestors. *Appl Microbiol Biotechnol.* 1995;43:559-565.

103. Kim JK, Oh BR, Chun YN, Kim SW. Effects of temperature and hydraulic retention time on anaerobic digestion of food waste. *J Biosci Bioeng.* 2006;102:328-332.

104. Kan T, Strezov V, Evans TJ. Lignocellulosic biomass pyrolysis: a review of product properties and effects of pyrolysis parameters. *Renew Sustain Energy Rev.* 2016;57:1126-1140.

105. Grycová B, Koutník I, Pryszcz A. Pyrolysis process for the treatment of food waste. *Bioresour Technol.* 2016;218:1203-1207.

106. Bridgewater AV. Review of fast pyrolysis of biomass and product upgrading. *Biomass Bioenergy.* 2012;38:68-94.

107. Bridgewater AV, Meier D, Radlein D. An overview of fast pyrolysis of biomass. *Org Geochem.* 1999;30:1479-1493.

108. Milne T, Agblevor F, Davis M, Deutch S, Johnson D. A review of the chemical composition of fast-pyrolysis oils from biomass. In: Bridgewater AV, Boocock D, eds. *Dev Thermochem Biomass Convers.* Vols. 1/2. Dordrecht, Netherlands: Springer; 1997:409-424.

109. Patwardhan P. *Understanding the product distribution from biomass fast pyrolysis.* Graduate Theses and Dissertations. Paper 11767. http://www.researchgate.net/publication/51103578; 2010, (n.d.).

110. Goyal HB, Seal D, Saxena RC. Bio-fuels from thermochemical conversion of renewable resources: a review. *Renew Sustain Energy Rev.* 2008;12:504-517.

111. Montoya Arbeláez JJ, Chejne Janna F, García-Pérez M. Fast pyrolysis of biomass: a review of relevant aspects. Part I: parametric study. *Dyna.* 2015;82:239-248.

112. Figueiredo M, Fernando A, Martins G, Freitas J, Judas F, Figueiredo H. Effect of the calcination temperature on the composition and microstructure of hydroxyapatite derived from human and animal bone. *Ceram Int.* 2010;36:2383-2393.

113. Sekar S, Hottle RD, Lal R. Effects of biochar and anaerobic digester effluent on soil quality and crop growth in Karnataka, India. *Agric Res.* 2014;3:137-147.

114. Imam T, Capareda S. Characterization of bio-oil, syn-gas and biochar from switchgrass pyrolysis at various temperatures. *J Anal Appl Pyrolysis.* 2012;93:170-177.

115. Yang H, Yan R, Chen H, Lee DH, Zheng C. Characteristics of hemicellulose, cellulose and lignin pyrolysis. *Fuel.* 2007;86:1781-1788.

116. Chang F, Wang C, Wang Q, Jia J, Wang K. Pilot-scale pyrolysis experiment of municipal sludge and operational effectiveness evaluation. *Energy Sources, Part A Recover Util Environ Eff.* 2016;7036:472-477.

117. Huang Y, Jin B, Zhong Z, Zhong W, Xiao R. Characteristic and mercury adsorption of activated carbon produced by CO2 of chicken waste. *J Environ Sci.* 2008;20:291-296.

118. Burra KG, Hussein MS, Amano RS, Gupta AK. Syngas evolutionary behavior during chicken manure pyrolysis and air gasification. *Appl Energy.* 2016;181:408-415.

119. Yang H, Huang L, Liu S, Sun K, Sun Y. Pyrolysis process and characteristics of products from sawdust briquettes. *BioResources.* 2016;11:2438-2456.

120. Zhang B, Zhong Z, Xie Q, Liu S, Ruan R. Two-step fast microwave-assisted pyrolysis of biomass for bio-oil production using microwave absorbent and HZSM-5 catalyst. *J Environ Sci (China).* 2015;45:240-247.

121. Zhou H, Long Y, Meng A, Li Q, Zhang Y. Interactions of three municipal solid waste components during co-pyrolysis. *J Anal Appl Pyrolysis.* 2015;111:265-271.

122. Song X-D, Chen D-Z, Zhang J, Dai X-H, Qi Y-Y. Anaerobic digestion combined pyrolysis for paper mill sludge disposal and its influence on char characteristics. *J Mater Cycles Waste Manag.* 2015;19:332-341.

123. Jaroenksammeesuk C, Tippayawong N. Technical and Economic Analysis of A Biomass Pyrolysis Plant. *Energy Procedia.* 2015;79:950-955.

124. Liden AG, Berruti F, Scott DS. A kinetic model for the production of lipids from the flash pyrolysis of biomass. *Chem Eng Commun.* 1988;65:207-221.

125. Fagbohungbe MO, Herbert B, Hurst L, Li H, Usmani SQ, Semple KT. Impact of biochar on the anaerobic digestion of citrus peel waste. *Bioresour Technol.* 2016;216:142-149.

126. Westman S, Chandolias K, Taherzadeh M. Syngas biomethanation in a semi-continuous reverse membrane bioreactor (RMBR). *Fermentation.* 2016;2:8.

127. Kimmel DE, Klasson KT, Clausen EC, Gaddy JL. Performance of trickle-bed bioreactors for converting synthesis gas to methane. *Appl Biochem Biotechnol.* 1991;28:29-457.

128. Méndez A, Terradillos M, Gascó G. Physicochemical and agronomic properties of biochar from sewage sludge pyrolysed at different temperatures. *J Anal Appl Pyrolysis.* 2013;102:124-130.

129. Xu H, Giwa AS, Wang C, et al. Impact of antibiotics pretreatment on bioelectrochemical CH4 production. *ACS Sust Chem Eng.* 2017;5:8579-8586.

130. Luo C, Lü F, Shao L, He P. Application of eco-compatible biochar in anaerobic digestion to relieve acid stress and promote the selective colonization of functional microbes. *Water Res.* 2015;68:710-718.

131. Demirbas A. Biofuels sources, biofuel policy, biofuel economics and global biofuel projections. *Energy Convers Manag.* 2008;49:2106-2116.

132. Mulchhna M, Brocke F, Heeg K, Werner M. Use of biochars in anaerobic digestion. *Bioresour Technol.* 2014;164:189-197.

133. Xu H, Giwa AS, Wang C, et al. Impact of antibiotics pretreatment on bioelectrochemical CH4 production. *ACS Sust Chem Eng.* 2017;5:8579-8586.

134. Hübner T, Mumme J. Integration of pyrolysis and anaerobic digestion–use of aqueous liquor from digestate pyrolysis for biogas production. *Bioresour Technol.* 2015;183:86-92.

135. Mumme J, Strocke F, Heeg K, Werner M. Use of biochars in anaerobic digestion. *Bioresour Technol.* 2014;164:189-197.

136. Huber GW, Iborra S, Corma A. Synthesis of transportation fuels via pyrolysis and gasification: a review. *Appl Energy.* 2015;140:4044-4098.

137. Mohan D, Sarwat A, Ok YS, Pittman CU. Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent – a critical review. *Bioresour Technol.* 2014;160:191-202.

138. Kabouris JC, Tezel U, Pavlostathis SG, et al. Methane recovery from the anaerobic codigestion of municipal sludge and FOG. *Bioresour Technol.* 2009;100:3701-3705.
140. Pöschl M, Ward S, Owende P. Evaluation of energy efficiency of various biogas production and utilization pathways. Appl Energy. 2010;87:3305-3321.

141. Titiloye JO, Abu Bakar MS, Odetoye TE. Thermochemical characterisation of agricultural wastes from West Africa. Ind Crops Prod. 2013;47:199-203.

142. Munasinghe PC, Khanal SK. Biomass-derived syngas fermentation into biofuels: opportunities and challenges. Bioresour Technol. 2010;101:5013-5022.

143. Zhu X, Cao Q, Chen Y, Sun X, Liu X, Li D. Effects of mixing and sodium formate on thermophilic in-situ biogas upgrading by H₂ addition. J Clean Prod. 2019;216:373-381.

144. Shah S, Bergland WH, Bakke R. Methane from Syngas by Anaerobic Digestion; 2017:114-120.

145. Glaser B. Prehistorically modified soils of central Amazonia: a model for sustainable agriculture in the twenty-first century. Philos Trans R Soc B Biol Sci. 2007;362:187-196.

146. Zhao B, O’Connor D, Zhang J, et al. Effect of pyrolysis temperature, heating rate, and residence time on rapeseed stem derived biochar. J Clean Prod. 2017;174:977-987.

147. Manyà JJ. Pyrolysis for biochar purposes: a review to establish current knowledge gaps and research needs. Environ Sci Technol. 2012;46:7939-7954.

148. Smith M, Liaw S, Garcia-perez M. Integrating Pyrolysis and Anaerobic Digestion; 2012.

149. Li H, Feng K. Life cycle assessment of the environmental impacts and energy efficiency of an integration of sludge anaerobic digestion and pyrolysis. J Clean Prod. 2018;195:476-485.

150. Salman CA, Schwede S, Naqvi M, Thorin E. Synergistic combination of pyrolysis, anaerobic digestion, and CHP plants. Energy Procedia. 2019;158:1323-1329.

151. Andreoni V, Bonfanti P, Daffonchio D, Sorlini C, Villa M. Anaerobic digestion of wastes containing pyrolytic acids. Biol Wastes. 1990;34:203-214.

152. Ni MJ, Xiao G, Chi Y, et al. Study on pyrolysis and gasification of wood in MSW. J Environ Sci. 2006;18:407-415.

153. Cross WH, Chian E, Pohland FG. Anaerobic biological treatment of coal gasifier effluent. Biotechnol Bioeng Symp. 1982;12:349-363.

154. Wirth B, Mumme J. Anaerobic digestion of waste water from hydrothermal carbonization of corn silage. Appl Bioenergy. 2014;1:2018.

155. Henstra AM, Sipma J, Rinzema A, Stams AJ. Microbiology of synthesis gas fermentation for biofuel production. Curr Opin Biotechnol. 2007;18:200-206.

156. Salman CA, Schwede S, Thorin E, Yan J. Enhancing biomethane production by integrating pyrolysis and anaerobic digestion processes. Appl Energy. 2017;204:1074-1083.

157. Diender M, Stams A, Sousa DZ. Pathways and bioenergetics of anaerobic carbon monoxide fermentation. Front Microbiol. 2015;6:1-18.

158. Basu P, Basu P. Chapter 9 – Production of synthetic fuels and chemicals from biomass. In: Biomass Gasif Pyrolysis; 2010;301-323.

159. Przybyla G, Rei A, Silveira R, Willian C, Belli P. Potential use of methane and syngas from residues generated in rice industries of Pelotas. Rio Grande do Sul: Thermal and electrical energy. 2019:134.

160. Szuhaj M, Ács N, Tengölcs R, Bodor A, Rákhegy G, Kovács KL. Biotechnology for biofuels conversion of H₂ and CO₂ to CH₄ and acetate in fed-batch biogas reactors by mixed biogas community: a novel route for the power-to-gas concept. Biotechnol Biofuels. 2016;9:1-14.

161. Shanmugam SR, Adhikari S, Nam H, Kar Sajib S. Effect of biochar on methane generation from glucose and aqueous phase of algae liquefaction using mixed anaerobic cultures. Biomass Bioenerg. 2018;108:479-486.