Bioresource Technology 301 (2020) 122778

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Review

Resource recovery and circular economy from organic solid waste using aerobic and anaerobic digestion technologies

Steven Wainaina[b], Mukesh Kumar Awasthi[a,b,*], Surendra Sarsaiya[f], Hongyu Chen[d], Ekta Singh[c], Aman Kumar[c], B. Ravindran[e], Sanjeev Kumar Awasthi[a], Tao Liu[a], Yumin Duan[a], Sunil Kumar[c], Zengqiang Zhang[a], Mohammad J. Taherzadeh[b]

[a] College of Natural Resources and Environment, Northwest A&F University, Yangling, Shaanxi Province 712100, PR China
[b] Swedish Centre for Resource Recovery, University of Borås, 50190 Borås, Sweden
[c] CSIR-National Environmental Engineering Research Institute, Nehru Marg, Nagpur 440 020, Maharashtra, India
[d] Institute of Biology, Freie Universität Berlin Altensteinstr. 6, 14195 Berlin, Germany
[e] Department of Environmental Energy and Engineering, Kyonggi University Youngtong-Gu, Suwon, Gyeonggi-Do 16227, South Korea
[f] Key Laboratory of Basic Pharmacology and Joint International Research Laboratory of Ethnomedicine of Ministry of Education, Zunyi Medical University, Zunyi, Guizhou, PR China

A R T I C L E I N F O

Keywords:
Resource recovery
Organic solid waste
Circular economy
Anaerobic digestion
Composting

A B S T R A C T

With the inevitable rise in human population, resource recovery from waste stream is becoming important for a sustainable economy, conservation of the ecosystem as well as for reducing the dependence on the finite natural resources. In this regard, a bio-based circular economy considers organic wastes and residues as potential resources that can be utilized to supply chemicals, nutrients, and fuels needed by mankind. This review explored the role of aerobic and anaerobic digestion technologies for the advancement of a bio-based circular society. The developed routes within the anaerobic digestion domain, such as the production of biogas and other high-value chemicals (volatile fatty acids) were discussed. The potential to recover important nutrients, such as nitrogen through composting, was also addressed. An emphasis was made on the innovative models for improved economics and process performance, which include co-digestion of various organic solid wastes, recovery of multiple bio-products, and integrated bioprocesses.

1. Introduction

Disposal of organic solid waste (OSW) has become one of the hot topics in research. Simultaneously, the collection and recycling of OSW is presently principal environmental concerns in both urban and countryside areas in numerous industrial and developing countries (Vinay et al., 2018). With the rapid development of modern society and the continuously rising population all over the world, the generation of OSW is projected to be significantly increased annually. Statistically, 2.01 billion tons of municipal wastes were produced worldwide and by 2050, approximately 3.4 billion tons of municipal wastes will be emerged annually if the current trend continues (Luis et al., 2019). Furthermore, improper waste management is not only pernicious to human beings and local environment, but also exacerbates the climate change and causes the sanitation system thus forcing nations and governments to invest more financial and material resources for its remediation. Consequently, ideal technologies to OSW management is not only conducive to environmental protection and sustainable development but also critical to forge a circular economy (Felix et al., 2019).

In a circular economy, recycling and reuse is the major principle for designing and optimization of products. As nations and authorities all over the world gradually embracing the concept of circular economy and attempting to bring it in practice, disposing wastes with an advanced and sustainable way could promote efficient economic growth with reduced environmental impacts at the same time (Pooja et al., 2018; González-García et al., 2019). This concept not only creates more job opportunities but also able to converts waste into treasure and transforms it to a new clean energy and material sources through classified management and recycling. Governments and municipalities around the world have started paying great attention to it and constantly reform the urban wastes management system, making it an important part of the green economy and sustainable development (Biswabandhu et al., 2019). The majorities of OSW are composed of

* Corresponding author at: College of Natural Resources and Environment, Northwest A&F University, Yangling, Shaanxi Province 712100, PR China.
E-mail address: mukesh_awasthi45@yahoo.com (M.K. Awasthi).

https://doi.org/10.1016/j.biortech.2020.122778
Received 18 November 2019; Received in revised form 6 January 2020; Accepted 7 January 2020
Available online 10 January 2020
0960-8524/

Table 1
Wastes production by economic and household activities until 2016 on percentage basis.

Countries	Mining and quarrying	Manufacturing	Energy	Construction and demolition	Other economic activities	Households
EU-28	25	10	3	36	16	8
Belgium	0	23	1	31	36	8
Bulgaria	82	3	8	2	3	2
Czechia	1	18	4	40	23	14
Denmark	0	5	4	58	16	17
Germany	2	14	3	55	17	9
Estonia	26	37	25	5	6	2
Ireland	16	35	2	10	28	10
Greece	78	6	4	1	4	7
Spain	16	11	3	28	26	17
France	1	7	0	69	14	9
Croatia	12	8	2	24	31	22
Italy	0	17	2	33	29	18
Cyprus	5	33	0	36	10	16
Latvia	0	19	11	4	30	34
Lithuania	1	41	2	8	32	17
Luxemburg	0	7	0	75	11	6
Hungary	1	17	16	23	25	18
Malta	8	1	0	69	13	8
Netherlands	0	10	1	70	13	6
Austria	0	9	1	73	10	7
Poland	39	17	11	10	18	5
Portugal	3	17	1	12	35	33
Romania	87	4	4	0	3	2
Slovenia	0	26	14	10	38	12
Slovakia	3	32	9	9	29	18
Finland	76	8	1	11	3	1
Sweden	77	4	1	7	7	3
United Kingdom	6	4	0	49	30	10
Iceland	0	25	0	4	31	40
Liechtenstein	3	2	0	88	1	5
Norway	3	14	2	27	32	22
Montenegro	19	2	18	37	10	13
North Macedonia	49	51	0	0	0	0
Serbia	79	3	12	1	2	3
Turkey	11		26			37
Bosnia and Herzegovina	2	27	71	0	0	0
Kosovo	14	20	40	6	10	11

Source: Eurostat (online data code: env_wasgen), 2016.

animal wastes, municipal and agricultural wastes, thus OSWs are generally rich in nutrient substances, such as proteins, minerals, and sugars, which can be reused as raw materials in the production of green energy (Kiros et al., 2017). Nevertheless, due to the restrictions of the allocated budgets, infrastructure development, OSW management is still suffering from improper treatment in most developing and even in few developed countries. Therefore, the most decisive factors in OSW management is to develop an economically sustainable process followed by technically feasible, socially and legally acceptable as well as environment friendly. Hence, OSW management is usually one of the most important challenges for the authorities and a hot research topic all over the world (Alejandra et al., 2018). Based on the characteristics of the OSW, they are generally treated to be converted into organic fertilizer or directly transport to landfill sites or incineration facilities. Therefore, the conventional methods including landfill, incineration, and composting are traditional matured technologies for OSW management. Different processing technologies possess varied advantages and also drawbacks as well. On the other hand, biological technologies for OSW treatment are now-a-days seriously considered in the world because of the characteristics of low energy consumption, low cost and investment, high organic removal rate and meeting the requirement of circular economy (Nurul et al., 2018). However, due to the different economical possibilities of various countries and the OSW treatment technologies, traditionally, the most commonly applied technologies are still landfill in developing countries and incineration in most of the developed countries.

Composting and anaerobic digestion (AD) depend on the decomposition and degradation of organic matter in OSW to stable substances, such as humus and digestate could be applied to soil as a fertilizer or soil improvement if their qualities are at standard level. During the AD process, biogas that is rich in methane and carbon dioxide are produced, which could be used as a fuel for combustion in transport or energy production (Nuhaa, 2019). Meanwhile, though these two technologies are not new, they probably could have a key role in achieving circular economy objectives to divert OSW from landfill and incineration and improving the circularity of biological nutrients. However, there are still many practical and technical issues that need to be addressed in the application of these two biological treatment methods (Zhang et al., 2019). In Europe, 60 million tons of OSW could be potentially recycled by AD and composting technologies (Felix et al., 2019). This would save about one million tons of nitrogen and 20 million tons of organic carbon (Luis et al., 2019). At present, most of these nutrients are lost through landfilling organic waste. The European Commission reported that the European countries in average recycle only 5% of the total OSW. It is estimated that if a higher portion of OSWs could be recycled and reused, it could replace approximately 30% of the chemical fertilizer applied to soil, that means 1.8 million tons phosphate fertilizer every year (Luis et al., 2019).

OSW can be converted to vary products through different processing technologies, such as fertilizer, heat, clean fuel from AD, plant and soil food from composting as well as methane from landfill. Despite this, either composting or AD must be fully understood prior to their wider deployment. This review comprehensively describes the current generation state of the OSW and different disposal technologies, particularly for composting and AD and elaborating on the details of their treatment process and their environmental, social and economic applicability. Both of these two technologies are not completely economically feasible, because of which they have not been successful applied in many countries. A deep insight has been attempted in this paper to make a better understanding for the importance of its economic viability.

2. Organic solid waste generation

The constant increase of worldwide population to more than seven billion plus the continuous improvement of global welfare has resulted in a rapid increase of the daily consumption of resources and products, thus tremendous amount of recyclable wastes is generated (Alejandra et al., 2018). The generation of wastes per capita in most of the industrial countries are higher than developing countries, which is most likely connected to the socio-economic status of the country. Taking the EU as an example, EU-28 nations produced nearly 25.38 million tons of wastes through all the activities including economic and households in 2016. Amongst it, the specific waste output of each EU nation also illustrated that the total amount of wastes generated had a certain degree of negligible relationship with the economic scale and population of a nation (Forough et al., 2019). It can be clearly observed from Table 1 that the EU member states with the smallest population and area possessed the lowest waste generation, oppositely the large nations owned the highest production. However, Italy had a relatively high amount of wastes generation, while Bulgaria and Romania possessed relatively low level of waste.

It is reported that in urban and rural areas of EU and other Asia countries, the level of solid wastes generation ranges from 0.9 to 1.6, and 0.7 to 1.5 kg per capita per day, respectively while the urban areas generate approximately 1.3 billion tons of solid wastes in 2015. It is estimated that it will increase to 2.2 billion tons by 2025 (WBA, 2017). Generally, the produced solid wastes are composed by agricultural and industrial wastes including leather, wood, glass, paper, green waste biomass, household wastes, and electronic wastes, such as computers, telephones, refrigerators, and televisions as well as also construction, demolition wastes and medical wastes (Munawar et al., 2019). As mentioned above, in most of the developing countries, the massive population growth and the acceleration of urbanization as well as the continuous improvement of people's living standards have significantly resulted in increasing the amount of urban wastes. The population all over the world was about 7.2 billion in 2013 and it will reach to 9.6 billion by 2050 (Biswabandhu et al., 2019). The population in urban areas is prognosed to account for 86% and 64% of the total population in developed and developing countries, respectively (Silva et al., 2019). Meanwhile, the dramatic increase of urban population will also result in infrastructural and strategic challenges as well as adverse land-use changes. Waste to energy technologies could turn as wise choices to deal with these circumstances and provide long-term and cost-effective solutions for the growing energy requirements and sustainable waste management. It is estimated that only from the global urban waste collection market can produce around $410 billion income (Waste Management World, 2017). However currently, only a quarter of wastes are recycled. Hence, recycling and utilizing OSW by applying biotechnologies has great bright prospects and market in the near future (Kiros et al., 2017).

3. Current organic solid waste treatment technologies

Various options are available for converting organic solid wastes into useful resources. Although pure cultures are ideal or synthesizing chemicals at high specificity and thus requiring minimal purification prior to final use, they require single substrates in the form of e.g. sugars. This has major drawbacks as it raises the cost of production and also competes for resources required for growing food and feed for humans and animals, thus raising ethical debates. Natural mixed bacterial consortia are therefore an attractive option for treating the abundantly available heterogeneous solid wastes and enables resource recovery in the form of energy and high-value platform chemicals through anaerobic digestion. These bacterial systems are also robust and have the capacity to withstand stressful micro-environments. Among the biological solid waste treatment possibilities provided in this section, only the production of biogas has been widely commercialized. The other products of ADs are mainly at research stage, providing opportunities for further scientific investigations and development (Wainaina et al., 2019a).

3.1. Biogas production

AD is an established biological processing technique suitable for stabilizing a plethora of organic solid wastes coupled with recovery of energy and nutrients. It provides a sustainable option for providing renewable materials and fuels thereby contributing to circular economy (Antoniou et al., 2019). Indeed, there are indications of that the biogas industry is steadily growing due to apparent substantial reduction of the capital and operating costs of AD facilities. Indeed, it has been estimated that the cost of production of biogas in AD facilities would reduce by about 38% in 2050 compared to 2015 (Ecofys, 2018). Globally, it the estimated that biogas production had an average growth rate of 11.2% reaching up to 58.7 billion Nm^3 in 2017 (WBA, 2017).

The AD process takes place in oxygen-deficient environments and is catalyzed by natural microbial communities in a four-stage complex process, resulting into mainly biogas. A pretreatment step, carried out either biologically, chemically or physically, can precede the actual biodegradation process in order to adequately prepare substrates with difficult structures such as lignocelluloses (Taherzadeh and Karimi, 2008; Sarsaiya et al., 2019a). The AD process kinetics are determined by the nature of substrates and the physico-chemical parameters, such as the pH, temperature and hydraulic retention time (Weiland, 2010). The details of the reactions taking place during the breakdown of the solid wastes during AD are provided in previous reviews (Aryal et al., 2018; Merlin Christy et al., 2014; Weiland, 2010). In summary, in the first stage hydrolytic microbes break down the complex macromolecules into simple monomers with the help of enzymes such as amylases, lipases, and proteases. The second stage applies acidogenic microbes and converts the soluble products produced in the first step into biomolecules, such as alcohols, volatile fatty acids (VFAs), hydrogen (H_2) and carbon dioxide (CO_2). These products then serve as substrates for acidogens for synthesis of mainly acetic acid in the third stage. The final stage is the most sensitive and greatly relies on the success of the previous reactions in which methanogens convert acetic acid, hydrogen and carbon dioxide into biogas. The methanogens follow mainly the acetotrophic (aceticlastic) and Wood Ljungdahl pathways for production of CH_4 from acetic acid and the reaction between H_2 and CO_2, respectively, with the latter being more common (Aryal et al., 2018; Merlin Christy et al., 2014; Rusmanis et al., 2019).

The chemical composition of raw biogas from a typical solid waste AD facility is based on the process conditions. It consists of 50 – 75% CH_4, 30 – 50% CO_2, 0 – 3% N_2, ~6% H_20, 0 – 1% O_2, 72 – 7200 ppm H_2S, 72 – 144 ppm NH_3 and other minor impurities (Kapoor et al., 2019; Yentekakis and Goula, 2017). The raw biogas can be directly applied for generating electricity and heat while upgraded gas (biomethane) can be injected into the natural gas grid or used as vehicle fuel (Fig. 1). The latter application has been reported to having the potential of aiding in reducing road transport - related greenhouse gas (GHG) emissions by up to 25% (Olsson and Fallde, 2015). In order to use the biogas as a transport fuel, an extra treatment is required for removal of CO_2 and other impurities, such as H_2S and water vapor. Gas cleaning is the initial step for removal of impurities that could damage mechanical and electrical appliances during the use of biogas and can be achieved using adsorption with silica gel and activated carbon or molecular sieves. Upgrading techniques mainly for separation of CO_2 from CH_4 in order to raise the calorific value of the gas are water

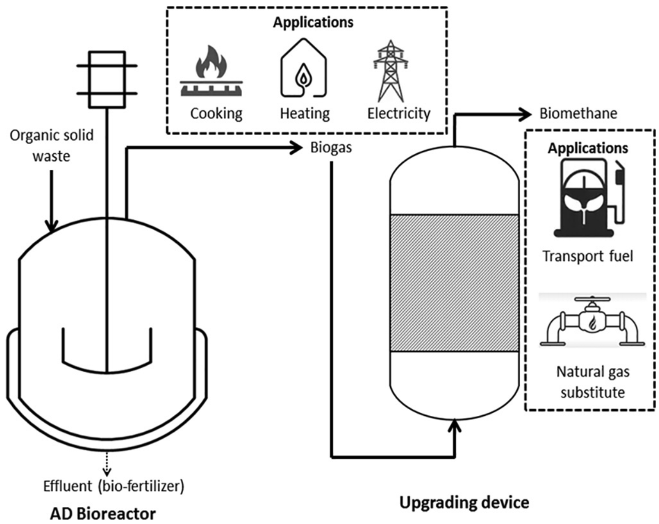

Fig. 1. Potential feed stock, conversion technologies and products.

scrubbing, pressure swing adsorption, cryogenic technology, membrane separation and organic scrubbing using amines such as diethanolamine, diglycolamine and monoethanolamine (Kapoor et al., 2019).

3.2. Hydrogen production

Energy recovery from solid wastes can also be achieved via the dark fermentation process. Compared to the conventional production routes such as steam reforming of methane and non-catalytic partial oxidation of fossil fuels, production of hydrogen from wastes not only reduces the reliance on the depleting petroleum resources but at the same time it is less energy-intensive as well (Kapdan and Kargi, 2006). Hydrogen has a higher heating value compared to methane (120 vs. 50 MJ/kg) (Liu et al., 2013). It's thus a potential clean energy source especially for the transport industry. Its other areas of application include production of electronics, processing of steel as well as hydrogenation of fats and oils (Kapdan and Kargi, 2006). A number of organic solid wastes that have been explored for hydrogen production are provided in Table 2.

The dark fermentation process is principally an intermediate within the AD process in which hydrogen is released. Thus, relevant parameters suitable for biosynthesis of hydrogen while at the same time deactivating the methanogens that would otherwise consume it are optimized (Kapdan and Kargi, 2006). Some of the important process parameters for ideal hydrogen production include the pH level, temperature and bioreactor design. Fang and Liu (2002) reported an optimal pH level of 5.5 while mesophilic and thermophilic temperature ranges were found to stimulate hydrogen production from wastes compared to psychrophilic conditions (Wang and Wan, 2008; Wang and Wan, 2009). Hydrogen fermentation systems also require appropriate bioreactor design to supply necessary hydrodynamic properties such as sufficient mixing (Ren et al., 2011). It is worth mentioning that the presence of other by-products, such as volatile fatty acids (VFAs) at certain concentrations can negatively impact on the microbial hydrogen production due to potential inhibition or even the depletion of hydrogen associated with formation of some VFAs. Potential solutions, such as the use of membrane bioreactors, have been proposed as effective in removing the VFAs as they are being formed and thereby improving the gas production (Trad et al., 2015).

3.3. Production of soluble biochemicals

3.3.1. Volatile fatty acids

VFAs are short-chain aliphatic carboxylic acids also formed as intermediaries during the AD process before the methanogenesis stage and consist between 2 and 6 carbon atoms. Petroleum resources are currently utilized for industrial synthesis of VFAs and replacing these resources with solid wastes as the primary feedstock creates and attractive circular economy pathway. The success of the acidification in AD reactors depends on optimization of operating parameters, such the pH, temperature, organic loading rate (OLR) and the hydraulic retention time (HRT) as well as employing appropriate means to deactivate the methanogenic VFAs-consumers (Atasoy et al., 2018; Lim et al., 2008, Wainaina et al., 2019a). Table 3 gives the performance of some waste-to-VFAs systems.

These acids have the potential for use as building blocks in a wide spectrum of industrial processes. For instance, acetic acid can be applied in pharmaceutical industries, propionic acid for manufacture of paints, butyric acid for manufacture of perfumes while caproic acid is used for preparation of food additives. The mixed solution of these VFAs also has important applications in wastewater treatment plants for biological removal of nitrogen and phosphorus, biosynthesis of mixed alcohols as well as production of biodegradable plastics. Moreover, the VFAs can be applied to generate electricity in microbial fuels cells in addition to serving as the carbon source for bioprocessing of biodiesel (González-García et al., 2019).

In order to facilitate practical production systems, recovery and purification of VFAs from fermentation broths are crucial. This involves primary separation of the liquid VFA fraction from the solid contents in the bioreactor made up of the cells and nutrients, which might be sufficient for some applications. However, for some application areas, more complex fractionation is needed for attaining the strict purity requirements. Adsorption, gas stripping and electrodialysis are examples of relevant methods proved to be effective in separation of the VFAs in model carboxylate solutions (Atasoy et al., 2018). Some researchers have also designed systems with the recovery procedure running concurrently with the actual microbial process in the so-called *in situ* product recovery using membrane-aided techniques (Arslan et al., 2017; Wainaina et al., 2019b). The benefits of such schemes are the supply of the carboxylates for subsequent processing without introduction of foreign soluble chemicals, in addition to the relief on the microbes from potential harmful effects of un-dissociated acid molecules.

3.3.2. Lactic acid

Lactic acid is a carboxylate with a market potential of USD 3.82 billion by 2020 used for production of acrylic acid, biodegradable polymers, pyruvic acid, 1, 2-propanediol, among others (Bonk et al., 2017; Phanthumchinda et al., 2018). Its main area of application is as a building block for poly (lactic acid) which has a high estimated market value of USD 5.16 billion by 2020 due to the mounting ecological concerns and supportive government policies (Phanthumchinda et al., 2018). A significant portion of the global industrial production is from fermentation, which is controlled by factors such as pH, temperature and nitrogen concentration (Alves de Oliveira et al., 2018).

The lactic acid bacteria (LAB) are popular for processing single sugars into lactic acid. In the AD systems, a variety of organic residues, such as food wastes and organic fraction of municipal solid waste, can be processed using microbes such as *Lactobacilli* during the acidogenic phase (Gu et al., 2018; Probst et al., 2015). Gu et al. (2018) for instance achieved a lactic acid buildup of up to 74.3% in a leach bed reactor treating food waste. Another research by Bonk et al. (2017) developed an AD reactor coupled with a percolation system which yielded lactic acid at 0.15 g chemical oxygen demand equivalent per g total solids fed ($gCOD/gTS_{fed}$) from food waste with lactic acid concentration of up to 16.4 g COD/L. As with the VFAs, appropriate product separation and purification methods are required to enhance the purity of lactic acid. One of the possible efforts involved a membrane-assisted lactic acid recovery method that incorporated microfiltration for cell removal, ultrafiltration for protein removal, and reverse osmosis for concentrating the lactic acid at high purity (Phanthumchinda et al., 2018).

Table 2
Potential organic waste substrates and optimal conditions for hydrogen production.

Substrate	Operating conditions	Hydrogen production performance	Reference
Melon waste	Continuous fermentation T = 55 °C HRT = 5 days pH = 5.0	Yield = 352 mL/gVS$_{added}$	Akinbomi and Taherzadeh (2015)
Melon waste	Batch essay T = 36 °C pH = 5.5 – 6.0	Productivity = 351.12 mLH$_2$/L$_{reactor}$.h	(Turhal et al., 2019)
Apple waste	Continuous fermentation T = 55 °C HRT = 5 days pH = 5.0	Yield = 635 mL/gVS$_{added}$	Akinbomi and Taherzadeh (2015)
Mixed food waste	Continuous fermentation T = 55 °C HRT = 5 days pH = 5.5	Yield = 1.80 mol-H$_2$/mol-hexose	Shin et al. (2004)
Mixed food waste	Batch essay T = 55 °C Initial pH = 7.0	Yield = 176.10 mL H$_2$/gCOD	Wongthanate and Mongkarothai (2018)
Waste peach pulp	Batch essay T = 37 °C Initial pH = 5.9	Productivity = 35.6 mLH$_2$/h	Argun and Dao (2017)
Fruit and vegetable waste	Batch essay T = 55 °C Initial pH = 7.0	Yield = 76 mL H$_2$/g VS	Keskin et al. (2018)
Waste bread	Continuous fermentation T = 55 °C HRT = 6 h pH $^>$ 4.0	Production rate = 7.4 LH$_2$/L/d	Han et al. (2016)

Table 3
Potential organic waste substrates and optimal conditions for production of volatile fatty acids.

Solid waste	Optimal conditions	Production performance	Reference
Olive mill solid waste	Batch-fed fermentation T = 35 °C pH = 9.0	Concentration = 3.69 gCOD/L	Cabrera et al. (2019)
Mixed food waste	Semi-continuous fermentation* T = 37 °C HRT = 6.67 days OLR = 2 gVS/L/d pH = 3.6 – 4.1	Yield = 0.54 gVFA/VS$_{fed}$	Wainaina et al. (2019a)
Mixed food waste	Semi-continuous fermentation T = 35 °C HRT = 12 days pH = 5.5	Yield = 0.39 gVFA/VS$_{fed}$	Lim et al. (2008)
Meat and bone meal	Batch fermentation T = 55 °C pH = 10.0	Yield = 0.46 gCOD/gCOD	Garcia-Aguirre et al. (2017)
Organic fraction of municipal solid waste	Continuous fermentation T = 55 °C HRT = 3.3 days OLR = 20.5 kgVS/m^3/d pH ≥ 4.0	Yield = 0.31 gCOD/gCOD$_{in}$VFA concentration = 16.0 gCOD/L	Valentino et al. (2018)
Waste activated sludge	Batch fermentation T = 21 °C pH = 10.0	Concentration = 2708.02 mg/L	Chen et al. (2007)

* A membrane bioreactor was used for simultaneous fermentation and product recovery.

3.3.3. *Other potential biochemicals*

The AD process also synthesizes other useful metabolites, although in low concentrations. According to Zhou et al. (2018), the possible metabolic pathways during the acidogenic biodegradation of wastes can lead to biosynthesis of other chemicals alongside VFAs, lactic acid and hydrogen. One such metabolite is succinic acid which can be applied in key industrial processes such as manufacture of inks, polymers and pharmaceuticals, and is bio-synthesized via the tricarboxylic acid cycle (TCA) (Isar et al., 2006). The use of pure microbes such as *Actinobacillus succinogenes* and an engineered *Escherichia coli* strain was found to effectively convert food waste hydrolysate into succinic acid (Sun et al., 2014). Concentrations of up to 8.5 g/L were detected during biodegradation of food waste at pH 5.0 (Lim et al., 2008). Such a performance indicates the potential for mixed bacterial consortium for metabolizing succinate that could be investigated in future studies. Ethanol has also been detected in small amounts from anaerobic digestion digesters. For instance, acidification of food waste yielded low concentrations at pH 6 and 7 (Xiong et al., 2019). In another study, Zhang et al. (2015) found that ethanol made up 33.8% of the liquid fraction during the thermophilic AD of glucose. One proposal to raise the concentration of ethanol by Zhou et al. (2018) would be providing high H_2 partial pressure in the head space of acidification reactors.

3.4. Nutrient recovery

The anaerobic digestion (AD) is considered as one of the foremost cost-effective biological treatments of the biowaste. It permits vitality recuperation and the generation of nutrient-rich digestate whereas lessening natural impacts of the waste transfer. It contains most of the supplements from the input material and can be utilized as fertilizer or organic amendment for farming. The natural supplement circle locally the digestate that needs to be utilized in ranches found adjacent to the mAD (micro-anaerobic digestion) units (Thiriet et al., 2020). The biowaste is utilized to provide vitality and recover other nutrients not only because it advances towards the financial conditions of a country, but besides makes a difference towards financial change of human society (Bhatia et al., 2018). Recognizably, the two forms, i.e., anaerobic digestion and composting, facilitates together since the solid fraction of digestate can be treated vigorously so as to recover both renewable energy and nutrients from common waste (Micolucci et al., 2016). These profitable nutrients display in natural strong waste which are efficiently misplaced, can be recovered through appropriate biochemical technologies and utilized as nutrient-rich fertilizers in rural areas for keeping up soil richness and arrive rebuilding hones at low-input premise. In this way, impressive emphasis is being focused on receiving biologically sound on best of financially maintainable and socially acceptable tools which reinforce potential recuperation of nutrients, with least contamination load (Soobhany, 2019). The final product, compost, may be a result of microbial action and contains mineral nutrients such as nitrogen, phosphorus and potassium (Fig. 2). Unfortunately, for nutrients recuperation it is exceptionally weak material in its raw form, but can contribute in 9.4% of P and 5% of N presented with inorganic fertilizers individually (Chojnacka et al., 2019).

Terax[TM] technology gives numerous opportunities for resource recovery such as changing over waste into value-added items, nutrient recuperation from natural waste, and metal expulsion from natural waste (Munir et al., 2018). There are still various challenge's heads for AnMBR stage applications to be handled, especially for extreme film fouling, moo methane substance in biogas, exceedingly broken-down methane, destitute smelling salts expulsion and phosphorus recuperation, etc. To address the above issues, a new-generation process (Fig. 6), i.e. so-called “Integrated Multistage Bio-Process (IMBP)” constituted of solar-driven bioelectrochemical framework (BES)-AnMBR, fractional nitritation/anammox (PN/A), nitrate decrease through anaerobic oxidation of methane (AOM) and biological/chemical phosphorus precipitation units have been examined in this article, with flexible capabilities in synchronous biowastes valorization, CO_2 electro-methanogenesis and synchronous biogas overhauling, *in-situ* fouling control, alkali expulsion, broken up methane reutilization, and phosphorus recoup as hydroxyapatite-rich supplements (Zhen et al., 2019).

3.5. Composting/co-composting

Composting process occurs naturally in the environment, although efficient composting is needed to control several factors to avoid environmental challenges such as odor and dust, and for obtaining a quality agricultural manure. Generally, composting process are divided into two phases, the bio-oxidative phase and the maturing phase also named as curing phase (Bernal et al., 1996). The bio-oxidative phase again carried out in three stages, such as initial activation, thermophilic and mesophilic or maturation phase. The organic waste degradation occurs during the thermophilic phase and microorganisms degrade the available compounds in the organic waste (Keener et al., 2000). In this phase, high temperature generation in the composting pile observed due to the heat generated from the composting pile due to the microbial degradation of organic waste (Sarsaiya et al., 2018). Generally, high temperature is required i.e. 55 °C to destroy pathogens in the organic solid waste and usually composting piles reach temperatures as high as 70 °C during the degradation of animal manure and green waste (Singh and Kalamdhad, 2014; Tang et al., 2011; Cáceres et al., 2015). In addition, in this stage the organic compounds degraded to CO_2 and NH_3 (Jeong et al., 2017; Kim et al., 2017), with the uptake of O_2. Finally, when the exhaustion of decomposable organic fraction in the waste

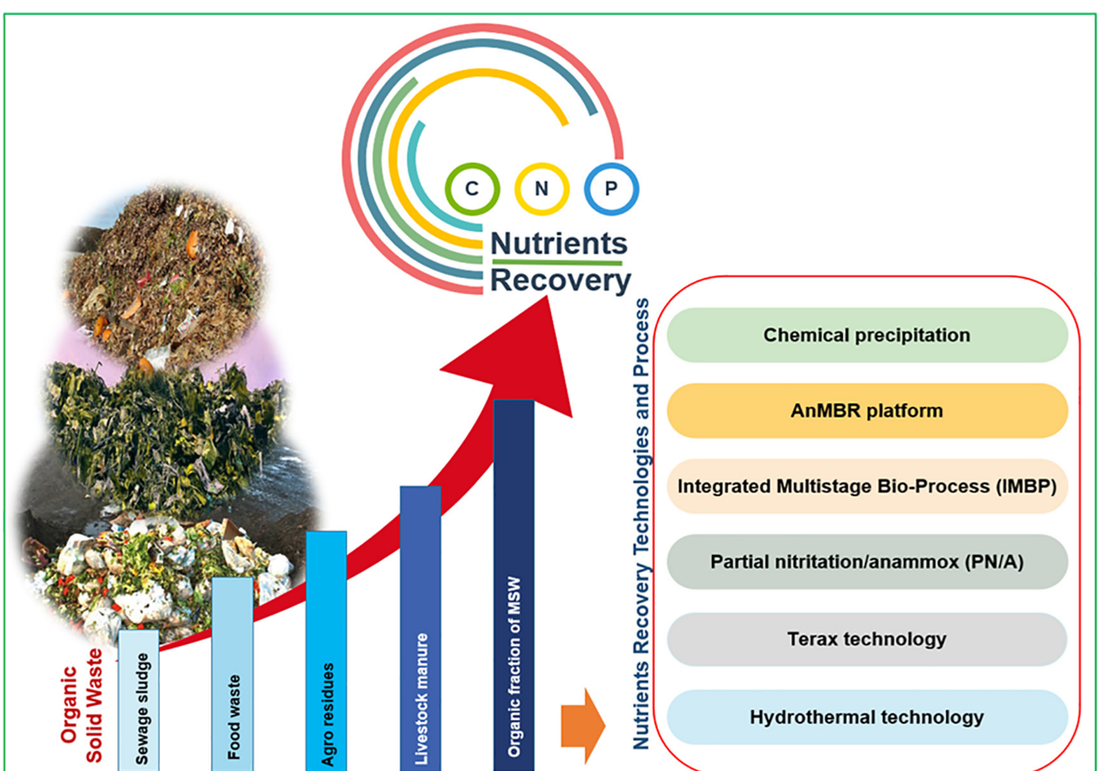

Fig. 2. Biogas production and the potential applications.

achieved, the temperature starts decreasing in the composting pile and hence beginning of the maturation phase observed and stabilization and humification of the organic matter occur, producing a mature compost with humic characteristics (Ravindran and Sekaran, 2010). Hence, this compost can be characterized as the stable and sanitized product that make the composting for sustainable agriculture and resource management (Haug, 1993; Ravindran et al., 2019; Gajalakshmi and Abbasi, 2008).

Over the last decades, researchers have been focusing on the study of the complex interaction between physical, chemical and biological factors that takes place during natural composting under controlled conditions. There are several factors affecting the composting process, such as nutrient balance, pH, porosity and moisture of the composting mixture, aeration, moisture content and temperature. Thus, the control of these parameters such as, porosity, nutrient content, C/N ratio, temperature, pH, moisture and oxygen supply have established to be key factors for optimization of composting process as they determine the optimal conditions for organic matter degradation and microbial growth (Agnew and Leonard, 2003; Das and Keener, 1996; Haug, 1993; Richard et al., 2002). The effectiveness of compost material with regard to their beneficial effects on agricultural as a nutrient source, depends on the quality of the compost. The quality criteria for compost material are determined by their nutrient content, organic matter stabilization, presence of heavy metals and toxic compounds.

The traditional composting process results in partial decomposition, which has phytotoxic effects in the final product (Ravindran et al., 2014). In order to overcome the conventional composting limitations, several researchers have employed an in-vessel composting strategy for different types of waste such as fly ash with organic waste (Mandpe et al., 2019); swine manure (Awasthi et al., 2019a; Yang et al., 2019; Ravindran et al., 2019); municipal solid waste (Malinowski et al., 2019); sewage sludge (Jain et al., 2019). An in-vessel composting system provides a controlled environment, which eliminates some of the obstacles inherent in traditional composting systems for producing nutrient rich matured manure. Despite that, environmental concerns related to composting existed, and can be categorized into three aspects described below;

3.5.1. Residual pollutants from contaminated feedstocks

Due to the existing contaminants in the feedstock, the levels of residual pollutants partly determined the feasibility of composting in field utilization. Such contaminants include heavy metals, organic pollutants, and emerging contaminants. Heavy metals refer to metallic chemical elements that had a higher density and 4.5 cm^3. Due to the high toxicity, long persistence, and bio-magnification traits, heavy metal accumulation in soils have become a global issue (Yang et al., 2017). Feedstock for composting, such as animal manure or sewage sludge, generally contain a certain amount of heavy metals, and these metals would be concentrated in the compost with the degradation of an organic compound, although the bio-availability is reduced (Li et al., 2012). For example, a nationwide survey on heavy metal content in compost derived from animals manures found the concentration of Zn, Cu, Cr, Ni, Pb, As, Co, Cd, and Hg ranged from 11.8 to 3692, 3.6 to 916, 0.7 to 6603, 0.7 to 73, 0.05 to 189, 0.4 to 72, 0.1 to 94, 0.01 to 8.7, and 0.01 to 1.9 mg kg^{-1}, respectively (Yang et al., 2017). There were even higher levels of heavy metals in other feed stock's like sewage sludge (Awasthi et al., 2017, 2018). Accordingly, government across different countries have introduced strict standard to regulate the maximum permissible values for organic compost.

Organic pollutants such as polycyclic aromatic hydrocarbons (PAHs) such as polychlorinated biphenyl (PCB), pesticides, and petroleum were generally found in compost (Ren et al., 2018; Houot et al., 2012). Even though the concentrations of such pollutants were generally reduced through composting via biodegradation, the concentration of residual organic pollutants might be higher than the background levels, which means inputs of such compost should be limited (Brandli et al., 2007). The other residues pollutants are antibiotic resistance genes and emerging contaminants such as micro particle, hormone, and perfluorinated compounds (PFCs). There were also high content of antibiotic in the common feedstock's of composting (i.e., sludge and manures), and studies focused on the fate of antibiotics and antibiotics resistance genes have become a research hotspot since 2009 (Ezzariai et al., 2018). However, studies on the transformation of antibiotic resistance genes are still limited, and the obtained results are partly contracted with each other (Wu et al., 2011; Wang et al., 2015). Therefore, more detailed research on the fate of antibiotic residence genes during composting should be further investigated.

3.5.2. Odors

During composting, series of stinky gases such as hydrogen sulfide, volatile organic sulfides, ammonia, pyridine, amines, hydrocarbons, terpenes, alcohols, ketones, aldehydes, and esters were generated (Wei et al., 2017). Additionally, the constitution and concentration of different compounds varied significantly and affected by the feed stock properties, composting operation conditions, and the ambient environment (Awasthi et al., 2018). Even though their concentrations are quite low, emission of odors gases can lead to significant allergy among the neighbor. Fortunately, we can significantly reduce the emission of odors nowadays by mediating ingredient properties, enhancing aeration, providing catalysts and inoculant, and building airtight composting facilities. More specifically, providing enzymatic catalysts on the surface of a compost pile or in the airspace above it can facilitate the biological reaction and eventually degrade the odorous compounds. Additionally, the addition of straw materials, chemical reagents (such as $FeCl_3$, lime, and MgO), and biochars can effectively prevent the emission of odors during composting (Ren et al., 2018; González et al., 2019).

4. Challenges and prospects of bio-based circular economy

The term "bio-based circular economy" can refer to an approach that promotes the reuse and valorization of organic wastes and residues. In the recent years, it has more essential options for the conversion of bio-waste and their intermediate products into bioenergy or secondary raw materials (Mohan et al., 2016).

4.1. Integrated organic solid waste treatments technologies

Rapid urbanization is surely creating enormous pressure on the urban bodies to deal with the demands of the developing populace and the consistently expanding huge amounts of waste all through the world (Awasthi et al., 2017; Zhou et al., 2014; Zhao et al., 2014). Because of lack of information and inappropriate waste gathering frameworks the untreated waste eventually arrives at the landfills and are responsible of aggravating the natural conditions. Inability in completely grasping all the issues identified with the management of municipal solid waste (MSW) ends up being one of the most challenging issues of degrading the environment. MSW contains a significant portion (30–50%) of organics (Bhattacharyya et al., 2008). The amount of each waste stream within the total solid waste generated varies with changes in specific parameters (Arafat et al., 2013).

At present, waste is viewed as an important asset rather than recognizing it to be useless and resource extraction from them is one of the primary goals of sustainable waste management (Kumar, 2017). A few treatment technologies are feasible with varying waste management abilities (Arafat et al., 2013). However, no single technique can fix the issue of waste management (Tehrani et al., 2009). Therefore, an integrated approach towards the treatment of solid waste is of great importance. It not just gives an adaptable waste treatment decision (organic or inorganic) but energy and asset recovery can likewise be effectively accomplished through it (Zhou et al., 2014). The significant reason behind treating the organic waste is to recover recyclables and

Fig. 3. Schematic presentation of integrated food waste and wastewater treatment method (MOWFAST) and conventional sludge (PSSS) treatment by anaerobic digestion (Extracted from Kaur et al., 2019).

energy from it and furthermore to improve the quality of the waste handling it (Fig. 3).

Organic solid waste treatment technologies may incorporate either a combination of mechanical, thermal or biological treatments or any of the three separately. The significant ones being the thermal and biological treatment techniques (Kumar, 2017). An integrated approach is certainly required which should be from its generation to its final disposal. The treatment procedure chosen ought to be such that it accomplishes the objectives of waste management. When the waste is explicitly organic in nature the biological procedures plays the main job, which are the aerobic and anaerobic digestion, bio-landfilling, biodrying and vermicomposting. Aerobic digestion transforms the easily degradable organic waste aerobically into soil conditioners and carbon dioxide with resulting heat production (Polprasert, 2007). Whereas anaerobic digestion involves degrading the organic waste anaerobically which leads to recovery of energy in form of biogas (Tchobanoglous et al., 2004). In this process, the organic waste gets decomposed by different microbial actions. However, in comparison to aerobic digestion, anaerobic digestion produces less solid sludge (Henze et al., 2008). Bio-landfilling is another procedure utilized for managing the solid waste that upgrades the waste degradation and also increases the measure of biogas formation (Davis and Cornwell, 2008). Anaerobic processing and bio-landfilling varies just in the utilization of reactor type which is simply the landfill itself during bio-landfilling. Bio drying is another such approach that aides in diminishing the measure of water present in the natural waste which would some way or another hamper the energy recuperation process (Polprasert, 2007). It additionally helps in saving energy for usage in residue derived fuels (Adani et al., 2002). All the major integrated organic waste treatment technologies discussed above have been shown in Fig. 3. All these technologies require a legitimate identification and assessment of accessible options, planning, collection, isolation, treatment and final disposal. In addition, understanding the potential interrelationships between various treatment options would help in building up an integrated approach where all the individual techniques supplement one another.

4.2. *Techno-economic feasibility of aerobic and anaerobic digestion technologies*

"Wastes from one industrial process can serve as the raw materials for another, thereby reducing the impact of industry in the environment" was described by Frosch and Gallopoulos (1989). Eco-industrial parks are making collaborate with other inter-company to optimize the resource efficiency. They can share the resources, water, and energy. Whereas working together, the community of businesses looking for collective benefits rather than individual benefits. Hence, the eco-industrial parks make industrial symbiosis for improvement of their economic status by sharing the raw materials and wastes. An anaerobic digestion process is a process, that can biochemically modify the whole biomass into specific components and this process can produce carbon dioxide, phosphorus and ammonia to improve the economic and environmental benefits. The biochemical processes in anaerobic digestion are nature. It is accepted and established as an innovative technology to produce the bio energy from whole biomass (Kavitha et al., 2017; Stiles et al., 2018).

An assessment of techno-economic analysis and life cycle are essential for any processes to be sustainable, which can be analysis by three parameters like economical viability, technical feasibility and environmental sustainability. There are number of industries and investors looking the production of biogas using anaerobic digestion method for generation of energy and a high-risk investment, because of its process like feedstock supply, segregation of solid waste, characteristics features of feedstock, profit issues and optional problems (Schmidt, 2014). Based on the above facts, the many governments have support and encourage by provide the funds to company for this area. According to Waste Management World (2017), the global biogas market will reach $50 billion on 2026, hence it is crucial for scientist and researchers to conduct their research on anaerobic digestion at systems level, as well as techno-economic and environmental benefits perspective. So, it is very essential to assess integrated analyses of economic viability and technical feasibility on anaerobic digestion technologies. The economic analysis for particular process is analyzed by values of materials for construction, interest rate and labor cost (Murthy, 2016). The techno-economic analysis and life cycle assessment (LCA) are providing the insights on the feasibility of a process and it is very important for bioenergy and bio-based products (Murthy, 2016). Techno-economic evaluation determines that maximum funds spent in biogas purification for various applications including the power-to-gas, electricity and vehicle fuel. Various anaerobic digester upgrading methods are available with membrane separation, water scrubbing, pressure adsorption and solvent scrubbing. Hence, the government has high cost for upgrading the anaerobic systems (Bauer et al., 2013; International Energy Agency, 2015).

Anaerobic co-digestion process is gradually more used to change the liquid and solid waste into nutrient rich content and reduce the impact of noxious compounds in the process and enhance the yield of biogas (Carlini et al., 2017). It is considered as the most important method for the management of biomass to production of biogas, and the digestate can be used as bio-fertilizer. This process can completely eliminate the pathogens (Sarsaiya et al., 2019b; Sarsaiya et al., 2019c) and to prevent the emission of greenhouse gases (Torquati et al., 2014; Weiland, 2010). United Kingdome and Hong Kong have strong-willed to sponsor the use anaerobic digestion methods for energy production and recovery. It also fulfils the Sustainable Development Goals (SDGs) for development of renewable energy (HK Policy address, 2017). In Italy, there are 35% of biogas plants that produce 70 – 100 MW electricity, which straight relate to government incentives (Gestore Servizi Energetici, 2015).

During the techno-economic analysis, three areas of anaerobic digestion process are important: (1) unit operations with collection and transport of feed stocks, (2) to provide the treatment facility for production of biogas, and (3) upgrading the bio-energy for various applications as electricity and liquid methane for household cooking. There is 20–50% of budget allotted to collect and transport the waste by manual collection or trucks/trailers in the sector of municipalities and corporations (Daniel and Perinaz, 2012). In Ireland, cost of $22 – 35/month was spent to waste collection from various sectors like houses and industries for anaerobic digestion (Koushki et al., 2004). Fig. 4 shows the cost associated with complete value chain of anaerobic digestion for solid waste.

4.3. Proposed models for a circular economy

4.3.1. Co-digestion

Biodegradation of more than one type of waste in one anaerobic bioreactor, albeit in appropriate proportions, is a promising technique for increasing product yields ascribed to the balance of nutrients that enhances microbial performance coupled with the economic benefits of treating a variety of materials in a single facility (Abad et al., 2019; Awasthi et al., 2019b; PagésDíaz et al., 2011). Several researchers have observed improvement of AD systems from a number of solid wastes demonstrating that anaerobic co-digestion, illustrated in Fig. 5a, could be a favorable method for achieving circular economy.

A study by Panichnumsin et al. (2010) reported that an increase of 41% in the specific methane yield would be realized when a cassava pulp/pig manure mixture was applied in the ratio of 3:2 relative to the use of pig manure alone. The potential cause of the improved performance was the improved process stability as well as an increase in the amounts of easily degradable macromolecules (Panichnumsin et al., 2010). In another study, improved buffering capacity and suitable carbon-to-nitrogen ratio were found to facilitate a stable AD process at high organic load even without regulation of pH when food waste and cattle manure were in ratio of 2:1 leading to an increase in the methane production by 55.2% compared to food waste alone (Zhang et al., 2013). The co-digestion strategy is also beneficial when targeting other AD bio-products such as H_2 and VFAs. A research by Zhou et al. (2013b) examined several mixtures containing food waste, primary sludge and waste activated sludge and concluded that co-digestion of the substrates improved hydrogen production compared to single substrates. The optimal increase was realized when a food waste/primary sludge/waste activated sludge mixture was applied at a ratio 80:15:5 (Zhou et al., 2013b). The impact of co-digesting waste activated sludge and corn straw was investigated by Zhou et al. (2013a). They observed an improvement in the maximum VFAs yield reaching up to 69% when a

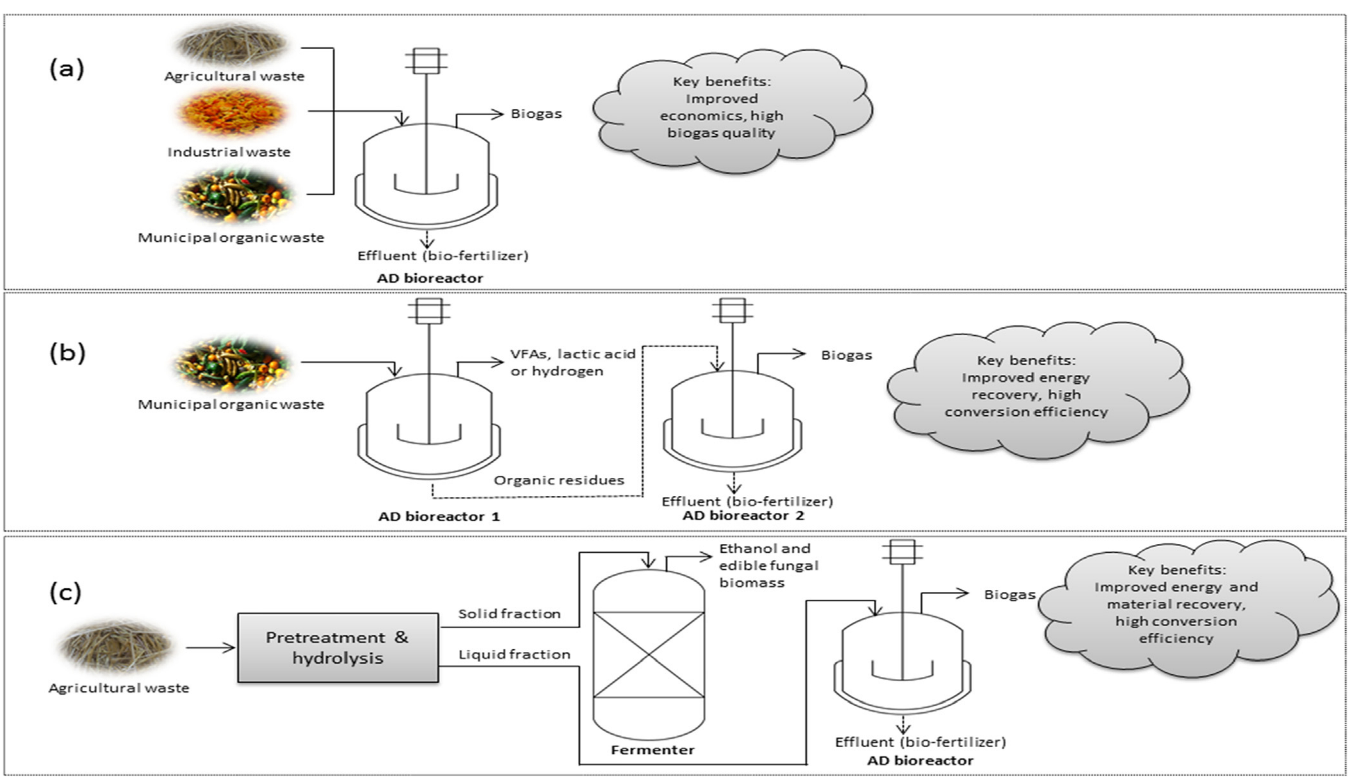

Fig. 4. Various costs associated with the value chain of waste treatment from collection to products generation. (Extracted from Rajendran and Murthy, 2019).

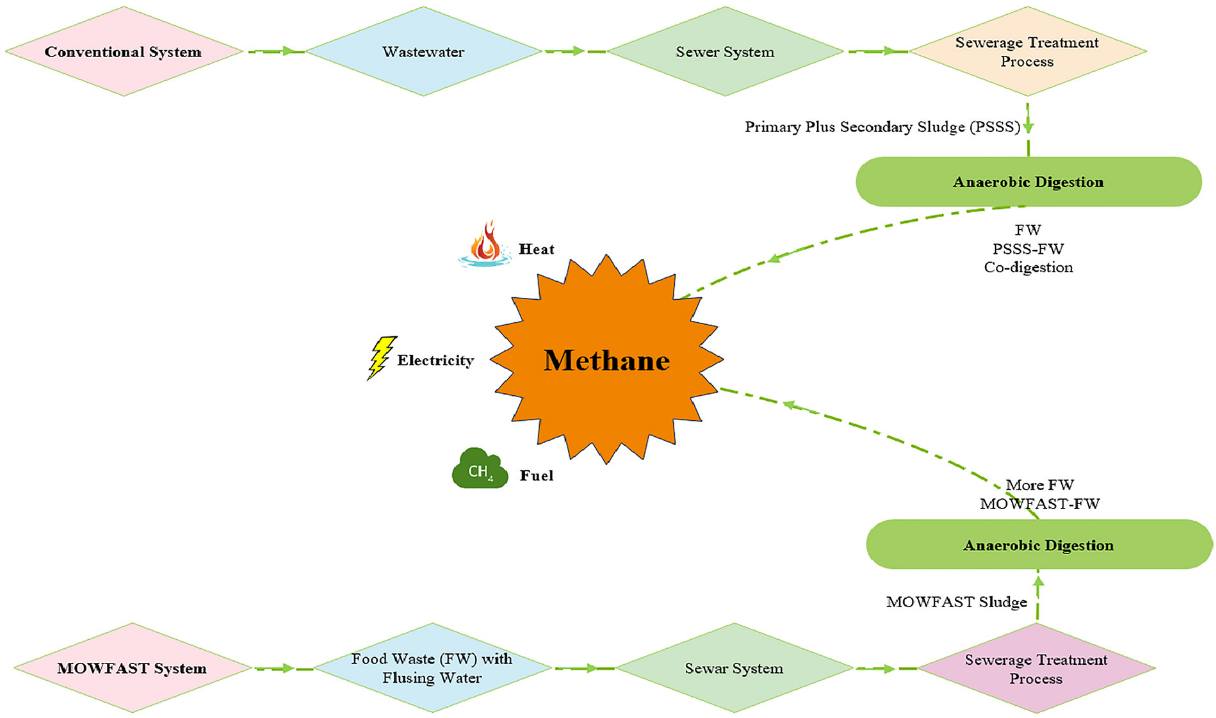

Fig. 5. Proposed models for circular economy using anaerobic digestion technology: co-digestion using municipal, industrial and agricultural wastes (a), recovery of multiple products (b) and integration of bioprocesses (c).

ratio of 1:1 of the mentioned substances was used compared to sludge only in addition to the manipulation of the product profile. Further results indicated that protein and carbohydrate consumption were enhanced by more than 120 and 220%, respectively (Zhou et al., 2013a).

Besides the conventional wet digestion, solid wastes can also be biodegraded at high total solids content of between 15 and 40% in the so-called dry AD processes using e.g. horizontal plug flow, sequential batch, textile-based, and vertical plug flow reactors. Dry AD is a promising technology for regions with low water availability and might also evade the pretreatment step for recalcitrant materials in addition to requiring more compact bioreactors (Awasthi et al., 2019a). An increase in methane yield of 14% was achieved when citrus wastes, chicken feather and wheat straw at a ratio of 1:1:6 in dry batch AD assays compared to single substrates. When the same substrate ratio was used in a continous plug flow bioreactor, a yield of 362 $NmLCH_4/gVS_{added}$ at a loading rate of 2 gVS/L/d was obtained (Patinvoh et al., 2018). Another dry AD process was demonstrated by Capson-Tojo et al. (2017) in which food waste and cardboard were co-digested in batch mode. Their research focused on the impact inoculum-to-substrate ratio which was found to have a significant influence on the methane yield, microbial dynamics as well as the productions of hydrogen and VFAs.

4.3.2. Recovery of multiple products

The AD process can be employed for the recovery of more than a single metabolite at reasonable yields, thereby increasing the process conversion efficiency (Fig. 5b). One of the possible scenarios was recently successfully executed involving the production of both VFAs and biogas from urban biowastes (organic fraction of municipal solid waste and waste activated sludge) in a pilot two-stage AD process (Valentino et al., 2019). The acidification reactor in the first stage operated at 37 °C generated VFAs up to at 19.5 g COD/L without external pH control. In the second stage, the solid-rich fraction collected from the acidification reactor was converted into biogas containing 63–64% CH_4 at a yield of up to 0.40 m^3/kg VS at 37 °C. Furthermore, it was claimed that a similar scaled-up system at the mentioned temperature would be thermally sustainable leading to a surplus of thermal energy in addition to an estimated revenue stream of 609,605 €/year from electricity (Valentino et al., 2019). Another scenario would involve the co-production of lactic acid and methane. Using organic fraction of municipal solid waste, Dreschke et al. (2015) designed a process to produce lactic acid in batch reactors at 37 °C. Lactic acid made up to 83% of the acid content with a yield of up to 37 g/kg was reached after 24 h. They also reported 75% *Lactobacilli* enrichment in the microbial consortium. The effluent from the batch fermenters were then co-digested with digested municipal sludge and a methane yield of up to 618 NmL CH_4/gVS was attained. In addition, the final effluent was proposed as a potential source of organic fertilizer (Dreschke et al., 2015).

In addition to the production of dissolved metabolites, it has been demonstrated the AD process can be applied for biosynthesis of both hydrogen and methane. The system can be optimized to yield the separate products in two distinct stages to produce a mixture known as hythane, which usually contains 10–25% hydrogen in methane (Liu et al., 2013; Wang et al., 2011). In addition to the possibility of effectively optimizing the separate processes, the other advantages of hythane production, relative to the single hydrogen or methane production, include the reduced overall fermentation time and the enhanced energy recovery (Liu et al., 2013). For instance, Siddiqui et al. (2011) observed that a single phase AD reactor resulted in 0.48 m^3/kgVS destroyed methane yield, while a two-phase process produced 0.67 m^3/kgVS destroyed methane in addition to hydrogen at a yield of 0.13 m^3/kgVS destroyed. Elsewhere when pulp and paper sludge and food waste (on a 1:1 mixing ratio based on the VS) were used, Lin et al. (2013) demonstrated a two-stage process in which hydrogen was produced in mesophilic conditions in stage one while the digestate from this stage was subjected to thermophilic AD conversion. They reported no accumulation of VFAs in the first reactor that yielded hydrogen up to 64.48 mL/gVS_{fed} at pH levels 4.8–6.4 while the methane yield was 432.3 mL/gVS_{fed} at pH levels 6.5–8.8 in the second reactor. In another research, Wang et al. (2011) co-digested cassava stillage and excess sludge in thermophilic conditions and found a 25% higher energy yield when a two-phase fermentation system was carried instead of a one phase system. By mixing cassava stillage and excess sludge at ratio of

3:1 (on VS basis) a hydrogen yield of 74 mL/gVS_{fed} and a methane yield of 350 mL/gVS_{fed} were attained.

4.3.3. Combined bioprocesses

Another strategy to implement systems that potentially meets the circular economy criteria involves combination of processes that are independently optimized to recover renewable energy, chemicals and materials (Fig. 5c). Successful demonstrations of such schemes mainly comprise established industrial processes involving the production of ethanol from lignocellulosic materials as the major activity. For instance, wheat straw was converted into three important products: ethanol, hydrogen and biogas (Kaparaju et al., 2009). The integrated bioprocess began with hydrothermal pretreatment of the wheat straw which resulted into cellulose-rich solid fraction and a hemicellulose-rich liquid fraction. The solid fraction was applied for ethanol fermentation in which a yield of up to 0.41 g/g-glucose was realized. Biogas was then produced using the effluent from the ethanol production processes yielding up to 0.324 m^3 CH_4/kg VS_{added}. The liquid fraction from the straw pretreatment was separately used in dark fermentation reactors and yielded up to 178.0 mL H_2/g-sugars. Similarly, the effluent from the hydrogen production processes was anaerobically digested to produce biogas at a yield of up to 0.381 m^3 CH_4/kg VS_{added}. Woody biomass has also been applied as a feedstock for production of both ethanol and biogas. Safari et al. (2016) during an investigation on the performance of dilute H_2SO_4 pretreatment of softwood pine demonstrated the potential improvements in the ethanol and biogas productions. Similar to the previously described work, the solid fraction from the pretreatment, consisting mostly of cellulose, was applied to produce ethanol production while the liquid fraction consisting of sugars was applied to produce biogas. The authors reported the highest ethanol yield of 53% while the highest biogas production yield was 162 m^3 methane/ton of pinewood. Another key outcome from their experiments showed that the inhibitory compounds released at the pretreatments at 180 °C had more negative impact on the production of biogas compared to the production of ethanol (Safari et al., 2016).

Another study was made by Wachendorf et al. (2009) proposed the use of silage for production of biogas and processing of a solid fuel as a potential feed stock for combustion or gasification. The silage was first subjected to hydrothermal conditioning and then mechanically dehydrated to separate the liquid from the solid portions. The former portion was used as substrate for production of biogas while the latter portion remained as a press cake (solid fuel). Moreover, the digestate from the anaerobic digester could be used as fertilizer for growing more silage, making the proposed scheme highly efficient in resource recovery (Wachendorf et al., 2009). In addition, a promising model that could be appropriate for agricultural wastes would be the simultaneous recovery of essential materials such as edible fungi. Nair et al. (2018) demonstrated an integrated bioprocess in which biogas, ethanol and protein-rich fungal biomass from pretreated wheat straw. *Neurospora intermedia* was the species applied for producing ethanol (yielding up to 90% of the theoretical maximum) as well as the biomass. Further results revealed that compared to untreated straw, an increase of up to 162% in the methane yield would be realized from the anaerobic treatment of the liquid stream from the pretreatment process. Besides, co-digestion assays of the mentioned stream with thin stillage, a waste stream from the ethanol production process, resulted in an increase in the total energy output of up to 27% (Nair et al., 2018).

5. Conclusion

This review paper evaluated resource recovery and circular economy options from organic solid waste using aerobic and anaerobic digestion technologies. Utilization of organic waste residues would elevate biorefinery concept and social acknowledgments. Aerobic and anaerobic digestion are widely acceptable technologies to enhance the efficiency for energy and other high value bio-based products production. Overall, various advanced models have recently been proposed and already worked out in line with a holistic biorefinery avenue that bring enormous industrial importance. Hence, the technoeconomic examination of these technologies is critically needed.

CRediT authorship contribution statement

Steven Wainaina: Dr. Steven is Investigation, and Methodology as well as write 60% part of this review article; **Mukesh Kumar Awasthi:** He has Conceptualization, design and Supervision of review and also writing - original draft this review article. In addition, Funding acquisition and Project administration; **Surendra Sarsaiya:** He has help to Data curation and Formal analysis; **Hongyu Chen:** He has help to Resources and Software, as well as write introduction and prepared Table 1; **Ekta Singh:** She has put some contribution to Resources and Software; **Aman Kumar:** He has put some contribution to Resources and Software; **B. Ravindran:** He has put some contribution to Validation and Visualization; **Sanjeev Kumar Awasthi:** He has put some contribution to data curation and Formal analysis; **Tao Liu:** He has put some contribution to data curation and Formal analysis; **Yumin Duan:** She has put some contribution to data curation and Formal analysis; **Sunil Kumar:** Dr. Kumar is Data curation and Formal analysis; **Zengqiang Zhang:** Prof. Zhang is Supervision, conceptualization and Funding acquisition; **Mohammad J. Taherzadeh:** Prof. Mohammad is Supervision, Validation, and Visualization, as well as very help to improve the manuscript quality and English.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by a research fund from the International Young Scientists from National Natural Science Foundation of China (Grant No. 31750110469), China; the Shaanxi Introduced Talent Research Funding (A279021901), China and The Introduction of Talent Research Start-up Fund (Grant No. Z101021904), College of Natural Resources and Environment, Northwest A&F University, Yangling, Shaanxi Province 712100, China. The Mobility for Regional Excellence-2020 (Grant No. RUN 2017-00771), European Union's Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie grant agreement No. 754412 at University of Borås, Borås, Sweden, and Guizhou Science and Technology Corporation Platform Talents Fund, China (Grant No.: [2017]5733-001 & CK-1130-002). We are also thankful to all our laboratory colleagues and research staff members for their constructive advice and help.

References

Abad, V., Avila, R., Vicent, T., Font, X., 2019. Promoting circular economy in the surroundings of an organic fraction of municipal solid waste anaerobic digestion treatment plant: biogas production impact and economic factors. Bioresour. Technol. 283, 10–17.
Adani, F., Baido, D., Calcaterra, E., Genevini, P., 2002. The influence of biomass temperature on biostabilization–biodrying of municipal solid waste. Bioresour. Technol. 83, 173–179.
Agnew, J.M., Leonard, J.J., 2003. The physical properties of compost. Compost Sci. Util. 1, 238–264.
Akinbomi, J., Taherzadeh, M.J., 2015. Evaluation of fermentative hydrogen production from single and mixed fruit wastes. Energies 8, 4253–4272.
Alejandra, C., Adriana, A., Xavier, F., Raquel, B., Teresa, G., Antoni, S., 2018. Composting of food wastes: status and challenges. Bioresour. Technol. 248, 57–67.
Alves de Oliveira, R., Komesu, A., Vaz Rossell, C.E., Maciel Filho, R., 2018. Challenges and opportunities in lactic acid bioprocess design-from economic to production aspects. Biochem. Eng. J. 133, 219–239.
Antoniou, N., Monlau, F., Sambusiti, C., Ficara, E., Barakat, A., Zabaniotou, A., 2019. Contribution to circular economy options of mixed agricultural wastes management:

coupling anaerobic digestion with gasification for enhanced energy and material recovery. J. Clean. Prod. 209, 505–514.
Arafat, H.A., Jijakli, K., Ahsan, A., 2013. Environmental performance and energy recovery potential of five processes for municipal solid waste treatment. J. Clean. Prod. 105, 233–240.
Argun, H., Dao, S., 2017. Bio-hydrogen production from waste peach pulp by dark fermentation: effect of inoculum addition. Int. J. Hydrogen Energy 42, 2569–2574.
Arslan, D., Zhang, Y., Steinbusch, K.J.J., Diels, L., Hamelers, H.V.M., Buisman, C.J.N., De Wever, H., 2017. In-situ carboxylate recovery and simultaneous ph control with tailor-configured bipolar membrane electro dialysis during continuous mixed culture fermentation. Sep. Purif. Technol. 175, 27–35.
Aryal, N., Kvist, T., Ammam, F., Pant, D., Ottosen, L.D.M., 2018. An overview of microbial biogas enrichment. Bioresour. Technol. 264, 359–369.
Atasoy, M., Owusu-Agyeman, I., Plaza, E., Cetecioglu, Z., 2018. Bio-based volatile fatty acid production and recovery from waste streams: current status and future challenges. Bioresour. Technol. 268, 773–786.
Awasthi, M.K., Liu, T., Chen, H., Verma, S., Duan, Y., Awasthi, S.K., Wang, Q., Ren, X., Zhao, J., Zhang, Z., 2019a. The behavior of antibiotic resistance genes and their associations with bacterial community during poultry manure composting. Bioresour. Technol. 280, 70–78.
Awasthi, M.K., Mahar, A., Ali, A., Wang, Q., Zhang, Z., 2017. Component technologies for municipal solid waste management. CRC Press. 178, 53–88.
Awasthi, M.K., Sarsaiya, S., Wainaina, S., Rajendran, K., Kumar, S., Quan, W., Duan, Y., Awasthi, S.K., Chen, H., Pandey, A., Zhang, Z., Jain, A., Taherzadeh, M.J., 2019b. A critical review of organic manure biorefinery models toward sustainable circular bioeconomy: technological challenges, advancements, innovations, and future perspectives. Renew. Sustain. Energy Rev. 111, 115–131.
Awasthi, M.K., Wang, Q., Awasthi, S.K., Wang, M., Chen, H., Ren, X., Zhao, J., Zhang, Z., 2018. Influence of medical stone amendment on gaseous emissions, microbial biomass and abundance of ammonia oxidizing bacteria genes during biosolids composting. Bioresour. Technol. 247, 970–979.
Bauer, F., Persson, T., Hulteberg, C., Tamm, D., 2013. Biogas upgrading – technology overview, comparison and perspectives for the future. Biofuel. Bioprod. Bior. 7, 499–511.
Bernal, M., Navarro, A., Roig, A., Cegarra, J., García, D., 1996. Carbon and nitrogen transformation during composting of sweet sorghum bagasse. Biol. Fert. Soils 22 (1–2), 141–148.
Bhatia, S.K., Joo, H.S., Yang, Y.H., 2018. Biowaste-to-bioenergy using biological methods - A mini-review. Energ. Convers. Manage. 177, 640–660.
Bhattacharyya, J.K., Kumar, S., Devotta, S., 2008. Studies on acidification in two-phase biomethanation process of municipal solid waste. Waste Manage. 28, 164–169.
Biswabandhu, C., Debabrata, M., 2019. Role of stage-separation in the ubiquitous development of Anaerobic Digestion of Organic Fraction of Municipal Solid Waste: a critical review. Renew. Sustain. Energy Rev. 104, 439–469.
Bonk, F., Bastidas-Oyanedel, J.R., Yousef, A.F., Schmidt, J.E., 2017. Exploring the selective lactic acid production from food waste in uncontrolled ph mixed culture fermentations using different reactor configurations. Bioresour. Technol. 238, 416–424.
Brandli, R.C., Bucheli, T.D., Kupper, T., Mayer, J., Stadelmann, F.X., Tarradellas, J., 2007. Fate of PCBs, PAHs and their source characteristic ratios during composting and digestion of source-separated organic waste in full-scale plants. Environ. Pollut. 148, 520–528.
Cabrera, F., Serrano, A., Torres, Á., Rodriguez-Gutierrez, G., Jeison, D., Fermoso, F.G., 2019. The accumulation of volatile fatty acids and phenols through a ph-controlled fermentation of olive mill solid waste. Sci. Total Environ. 657, 1501–1507.
Cáceres, R., Coromina, N., Malińska, K., Marfà, O., 2015. Evolution of process control parameters during extended co-composting of green waste and solid fraction of cattle slurry to obtain growing media. Bioresour. Technol. 179, 396–406.
Capson-Tojo, G., Trably, E., Rouez, M., Crest, M., Steyer, J.-P., Delgenès, J.P., Escudié, R., 2017. Dry anaerobic digestion of food waste and cardboard at different substrate loads, solid contents and co-digestion proportions. Bioresour. Technol. 233, 166–175.
Carlini, M., Mosconi, E., Castellucci, S., Villarini, M., Colantoni, A., 2017. An economical evaluation of anaerobic digestion plants fed with organic agro-industrial waste. Energies. 10, 1165.
Chen, Y., Jiang, S., Yuan, H., Zhou, Q., Gu, G., 2007. Hydrolysis and acidification of waste activated sludge at different pHs. Water Res. 41, 683–689.
Chojnacka, K., Gorazda, K., Witek-Krowiak, A., Moustakas, K., 2019. Recovery of fertilizer nutrients from materials - Contradictions, mistakes and future trends. Renew. Sustain Energy Rev. 110, 485–498.
Daniel, H., Perinaz, B.T., 2012. What a Waste: a Global Review of Solid Waste Management. World Bank.
Das, K., Keener, H.M., 1996. Dynamic simulation model as a tool for managing a large scale composting system. ASAE 6th Int. Computers in Agriculture, Cancum, Mexico.
Davis, M.L., Cornwell, A.D., 2008. Introduction to Environmental Engineering, fourth ed. McGraw Hill.
Dreschke, G., Probst, M., Walter, A., Pümpel, T., Walde, J., Insam, H., 2015. Lactic acid and methane: improved exploitation of biowaste potential. Bioresour. Technol. 176, 47–55.
Ecofys, 2018. Gas for Climate. How gas can help to achieve the Paris Agreement target in an affordable way. https://www.gasforclimate2050.eu/files/files/Ecofys_Gas_for_Climate_Feb2018.pdf. (Accessed: 02/09/2019).
Ezzariai, A., Mohamed, H., Ahmed, K., Quentin, A., Loubna, E.F., Maialen, B., Georges, M., Dominique, P., Eric, P., 2018. Human and veterinary antibiotics during composting of sludge or manure: global perspectives on persistence, degradation, and resistance genes. J. Hazard. Mater. 359, 465–481.
Fang, H.H.P., Liu, H., 2002. Effect of ph on hydrogen production from glucose by a mixed culture. Bioresour. Technol. 82, 87–93.
Felix, M., Ramchandra, B., Stefan, G., 2019. Critical review on life cycle assessment of conventional and innovative waste-to-energy technologies. Sci. Total Environ. 672, 708–721.
Forough, M., Keikhosro, K., Mohammad, J.T., 2019. Energy recovery from industrial crop wastes by dry anaerobic digestion: a review. Ind. Crop. Prod. 129, 673–687.
Frosch, D., Gallopoulos, N., 1989. Strategies for manufacturing. Sci. Am. 261, 144–1102.
Gajalakshmi, S., Abbasi, S.A., 2008. Solid waste management by composting: state of the art. Crit. Rev. Environ. Sci. Technol. 38, 311–400.
Garcia-Aguirre, J., Aymerich, E., González-Mtnez, deGoñi J., Esteban-Gutiérrez, M., 2017. Selective VFA production potential from organic waste streams: assessing temperature and pH influence. Bioresour. Technol. 244, 1081–1088.
Gestore Servizi Energetici (GSE), 2015. Incentivazione Delle Fonti Rinnovabili. Available online: http://www.gse.it/it/Dati%20e%20Bilanci/GSE_Documenti/Bollettino%20informativo Bollettino% 202%20semestre%202015.pdf. (accessed on 3 May 2017).
González-García, S., Rama, M., Cortés, A., García-Guaita, F., Núñez, A., Louro, L., Moreira, M., Feijoo, G., 2019. Embedding environmental, economic and social indicators in the evaluation of the sustainability of the municipalities of Galicia (northwest of Spain). J. Clean. Prod. 234, 27–42.
Gu, X.Y., Liu, J.Z., Wong, J.W.C., 2018. Control of lactic acid production during hydrolysis and acidogenesis of food waste. Bioresour. Technol. 247, 711–715.
Han, W., Huang, J., Zhao, H., Li, Y., 2016. Continuous biohydrogen production from waste bread by anaerobic sludge. Bioresour. Technol. 212, 1–5.
Haug, R.T., 1993. The Practical Handbook of Compost Engineering. Lewis Publishers, Boca Raton, FL.
Henze, M., Mark, C.M., van Loosdrecht, M.C., Ekama, G.A., 2008. Biological Wastewater Treatment, first ed. IWA Publisher, London, UK.
HK Policy Address. 2017. https://www.policyaddress.gov.hk/2017/eng/pdf/PA2017.pdf. (Accessed 13.01.18).
Houot, S., Verge-Leviel, C., Poitrenaud, M., 2012. Potential mineralization of various organic pollutants during composting. Pedosphere. 22, 536–543.
International Energy Agency, 2015. http://task37.ieabioenergy.com/plant-list.html.
International Standard Organization, 2006. ISO 14040: Environmental Management-Life Cycle Assessment-Principles and Framework.
Isar, J., Agarwal, L., Saran, S., Saxena, R.K., 2006. A statistical method for enhancing the production of succinic acid from escherichia coli under anaerobic conditions. Bioresour. Technol. 97, 1443–1448.
Jain, M.S., Paul, S., Kalamdhad, A.S., 2019. Interplay of physical and chemical properties during in-vessel degradation of sewage sludge. Waste Manage. 98, 58–68.
Jeong, K.H., Kim, J.K., Ravindran, B., Lee, D.J., Wong, J.W.C., Selvam, A., Karthikeyan, O.P., Kwag, J.H., 2017. Evaluation of pilot-scale in-vessel composting for Hanwoo manure. Bioresour. Technol. 245, 20–206.
Kaparaju, P., Serrano, M., Thomsen, A.B., Kongjan, P., Angelidaki, I., 2009. Bioethanol, biohydrogen and biogas production from wheat straw in a biorefinery concept. Bioresour. Technol. 100, 2562–2568.
Kapdan, I.K., Kargi, F., 2006. Bio-hydrogen production from waste materials. Enzyme Microb. Technol. 38, 569–582.
Kapoor, R., Ghosh, P., Kumar, M., Vijay, V.K., 2019. Evaluation of biogas upgrading technologies and future perspectives: a review. Environ. Sci. Pollut. R 26, 11631–11661.
Kaur, G., Luo, L., Chen, G., Wong, J.W.C., 2019. Integrated food waste and sewage treatment – A better approach than conventional food waste-sludge co-digestion for higher energy recovery via anaerobic digestion. Bioresour. Technol. 289, 121698.
Kavitha, S., Banu, J.R., Priya, A.A., Uan, D.K., Yeom, I.T., 2017. Liquefaction of food waste and its impacts on anaerobic biodegradability, energy ratio and economic feasibility. Appl. Energy 208, 228–238.
Keener, H.M., Dick, W.A., Hoitink, H.A.J., 2000. Composting and beneficial utilization of composted by-product materials. In: Dick, W.A., (Ed.), Land Application of Agricultural, Industrial, and Municipal By-Products. Soil Sci. Soc. Am. J. pp. 315-341.
Keskin, T., Arslan, K., Nalakth Abubackar, H., Vural, C., Eroglu, D., Karaalp, D., Yanik, J., Ozdemir, G., Azbar, N., 2018. Determining the effect of trace elements on biohydrogen production from fruit and vegetable wastes. Int. J. Hydrogen Energy 43, 10666–10677.
Kim, J.K., Lee, D.J., Ravindran, B., Jeong, K.H., Wong, J.W.C., Selvam, A., Karthikeyan, O.P., Kwag, J.H., 2017. Evaluation of integrated ammonia recovery technology and nutrient status with an in-vessel composting process for swine manure. Bioresour. Technol. 245, 365–371.
Kiros, H., Zong, J.P., Li, D.X., Liu, C., Lu, X.H., 2017. Anaerobic co-digestion process for biogas production: progress, challenges and perspectives. Renew. Sustain. Energy Rev. 76, 1485–1496.
Koushki, P., Al-Duaij, U., Al-Ghimlas, W., 2004. Collection and transportation cost of household solid waste in Kuwait. Waste Manage. 24, 957–964.
Kumar, S., 2017. Municipal solid waste management in developing countries. CRC press 178 -42B/W illustrations ISBN 978498737746-CAT# K26553.
Li, R., Wang, J.J., Zhang, Z., Shen, F., Zhang, G., Qin, R., Li, X., Xiao, R., 2012. Nutrient transformations during composting of pig manure with bentonite. Bioresour. Technol. 121 (121), 362–368.
Lim, S.J., Kim, B.J., Jeong, C.M., Choi, J.D., Ahn, Y.H., Chang, H.N., 2008. Anaerobic organic acid production of food waste in once-a-day feeding and drawing-off bioreactor. Bioresour. Technol. 99, 7866–7874.
Lin, Y., Wu, S., Wang, D., 2013. Hydrogen-methane production from pulp & paper sludge and food waste by mesophilic–thermophilic anaerobic co-digestion. Int. J. Hydrogen Energy 38, 15055–15062.
Liu, Z., Zhang, C., Lu, Y., Wu, X., Wang, L., Wang, L., Han, B., Xing, X.H., 2013. States and challenges for high-value biohythane production from waste biomass by dark

fermentation technology. Bioresour. Technol. 135, 292–303.
Luis, A.B.P., Barbara, S.B., Rafael, M.D., Daniel, J., Rosane, A.G.B., 2019. Organic solid waste management in a circular economy perspective - A systematic review and SWOT analysis. J. Clean. Prod. 239, 118086.
Malinowski, M., Wolny-Koładka, K., Vaverková, M.D., 2019. Effect of biochar addition on the OFMSW composting process under real conditions. Waste Manage. 84, 364–372.
Mandpe, A., Paliya, S., Kumar, S., Kumar, R., 2019. Fly ash as an additive for enhancing microbial and enzymatic activities in in-vessel composting of organic wastes. Bioresour. Technol. 293, 122047.
Merlin Christy, P., Gopinath, L.R., Divya, D., 2014. A review on anaerobic decomposition and enhancement of biogas production through enzymes and microorganisms. Renew. Sustain. Energy Rev. 34, 167–173.
Micolucci, F., Gottardo, M., Cavinato, C., Pavan, P., Bolzonella, D., 2016. Mesophilic and thermophilic anaerobic digestion of the liquid fraction of pressed biowaste for high energy yields recovery. Waste Manage. 48, 227–235.
Mohan, S.V., Nikhil, G.N., Chiranjeevi, P., Reddy, C.N., Rohit, M.V., Kumar, A.N., Sarkar, O., 2016. Waste biorefinery models towards sustainable circular bioeconomy: critical review and future perspectives. Bioresour. Technol. 215, 2–12.
Munawar, K., Mohammed, A.B., Rudi, H., Akhmad, R., 2019. Waste to energy technology: the potential of sustainable biogas production from animal waste in Indonesia. Renew. Sustain. Energy Rev. 105, 323–331.
Munir, M.T., Mansouri, S.S., Udugama, I.A., Baroutian, S., Gernaey, K.V., Young, B.R., 2018. Resource recovery from organic solid waste using hydrothermal processing: opportunities and challenges. Renew. Sustain. Energy Rev. 96, 64–75.
Murthy, G.S., 2016. Techno-economic assessment. In: Li, Y., Khanal, S.K. (Eds.), Bioenergy: Principles and Applications. Wiley-Blackwell, New Jersey, USA, pp. 507–520.
Nair, R.B., Kabir, M.M., Lennartsson, P.R., Taherzadeh, M.J., Horváth, I.S., 2018. Integrated process for ethanol, biogas, and edible filamentous fungi-based animal feed production from dilute phosphoric acid-pretreated wheat straw. Appl. Biochem. Biotech. 184, 48–62.
Nuhaa, S., 2019. Insight into the recovery of nutrients from organic solid waste through biochemical conversion processes for fertilizer production: a review. J. Clean. Prod., 118413.
Nurul, I.S., Zularisam, A.W., 2018. Achievements and perspectives of anaerobic co-digestion: a review. J. Clean. Prod. 194, 359–371.
Olsson, L., Fallde, M., 2015. Waste (d) potential: a socio-technical analysis of biogas production and use in Sweden. J. Clean. Prod. 98, 107–115.
PagésDíaz, J., Pereda Reyes, I., Lundin, M., SárváriHorváth, I., 2011. Co-digestion of different waste mixtures from agro-industrial activities: kinetic evaluation and synergetic effects. Bioresour. Technol. 102, 10834–10840.
Panichnumsin, P., Nopharatana, A., Ahring, B., Chaiprasert, P., 2010. Production of methane by co-digestion of cassava pulp with various concentrations of pig manure. Biomass. Bioenergy 34, 1117–1124.
Patinvoh, R.J., Lundin, M., Taherzadeh, M.J., SárváriHorváth, I., 2018. Dry anaerobic co-digestion of citrus wastes with keratin and lignocellulosic wastes: batch and continuous processes. Waste Biomass. Valori. 1–12.
Phanthumchinda, N., Thitiprasert, S., Tanasupawat, S., Assabumrungrat, S., Thongchul, N., 2018. Process and cost modeling of lactic acid recovery from fermentation broths by membrane-based process. Process Biochem. 68, 205–213.
Polprasert, C., 2007. Organic Waste Recycling Technology and Management, third ed. IWA, London, UK.
Pooja, Y., Samadder, S.R., 2018. A critical review of the life cycle assessment studies on solid waste management in Asian countries. J. Clean. Prod. 185, 492–515.
Probst, M., Walde, J., Pümpel, T., Wagner, A.O., Insam, H., 2015. A closed loop for municipal organic solid waste by lactic acid fermentation. Bioresour. Technol. 175, 142–151.
Rajendran, K., Murthy, G.S., 2019. Techno-economic and life cycle assessments of anaerobic digestion – A review. Biocat. Agric. Biotechnol. 20, 101207.
Ravindran, B., Contreras-Ramos, S.M., Wong, J.W.C., Selvam, A., Sekaran, G., 2014. Nutrient and enzymatic changes of hydrolysed tannery solid waste treated with epigeic earthworm. Environ. Sci. Pollut. Res. 21, 641–651.
Ravindran, B., Nguyen, D.D., Chaudhary, D.K., Chang, S.W., Kim, J., Lee, S.R., Shin, J., Jeon, B., Chung, S., Lee, J., 2019. Influence of biochar on physico-chemical and microbial community during swine manure composting process. J. Environ. Manage. 232, 592–599.
Ravindran, B., Sekaran, G., 2010. Bacterial composting of animal fleshing generated from tannery industries. Waste. Manage. 30, 2622–2630.
Ren, N., Guo, W., Liu, B., Cao, G., Ding, J., 2011. Biological hydrogen production by dark fermentation: challenges and prospects towards scaled-up production. Curr. Opin. Biotech. 22, 365–370.
Ren, Y., Yu, M., Wu, C., Wang, Q., Gao, M., Huang, Q., Liu, Y., 2018. A comprehensive review on food waste anaerobic digestion: research updates and tendencies. Bioresour. Technol. 1069–1076.
Richard, T.L., Hamelers, H.V.M., Veeken, A.H.M., Silva, T., 2002. Moisture relationships in composting processes. Compost. Sci. Util. 10, 286–302.
Rusmanis, D., O'Shea, R., Wall, D.M., Murphy, J.D., 2019. Biological hydrogen methanation systems – an overview of design and efficiency. Bioengineered 10 (1), 604–634.
Safari, A., Karimi, K., Shafiei, M., 2016. Integrated ethanol and biogas production from pinewood. RSC Adv. 6, 36441–36449.
Sarsaiya, S., Awasthi, S.K., Awasthi, M.K., Awasthi, A.K., Mishra, S., Chen, J., 2018. The dynamic of cellulase activity of fungi inhabiting organic municipal solid waste. Bioresour. Technol. 251, 411–415.
Sarsaiya, S., Jain, A., Kumar Awasthi, S., Duan, Y., Kumar Awasthi, M., Shi, J., 2019a. Microbial dynamics for lignocellulosic waste bioconversion and its importance with modern circular economy, challenges and future perspectives. Bioresour. Technol. 291, 121905.
Sarsaiya, S., Jia, Q., Fan, X., Jain, A., Shu, F., Lu, Y., Shi, J., Chen, J., 2019b. First report of leaf black circular spots on *Dendrobiumnobile* caused by *Trichodermalongibrachiatum* in Guizhou Province, China. Plant Dis. https://doi.org/10.1094/PDIS-03-19-0672-PDN.
Sarsaiya, S., Shi, J., Chen, J., 2019c. A comprehensive review on fungal endophytes and its dynamics on *Orchidaceae* plants: current research, challenges, and future possibilities. Bioengineered 10, 316–334.
Schmidt, T.S., 2014. Low-carbon investment risks and de-risking. Nat. Clim. Change 4, 237–239.
Shin, H.S., Youn, J.H., Kim, S.H., 2004. Hydrogen production from food waste in anaerobic mesophilic and thermophilic acidogenesis. Int. J. Hydrogen. Energy 29, 1355–1363.
Siddiqui, Z., Horan, N.J., Salter, M., 2011. Energy optimization from co-digested waste using a two-phase process to generate hydrogen and methane. Int. J. Hydrogen. Energy 36, 4792–4799.
Silva, R.V., Brito, J.D., Lynn, C.J., Dhirb, R.K., 2019. Environmental impacts of the use of bottom ashes from municipal solid waste incineration: a review. Resour. Conserv. Recycle 140, 23–35.
Singh, J., Kalamdhad, A.S., 2014. Potential for composting of green phumdi biomass of Loktaklake. Ecol. Eng. 67, 119–126.
Soobhany, N., 2019. Insight into the recovery of nutrients from organic solid waste through biochemical conversion processes for fertilizer production: a review. J. Clean. Prod. 241, 118413.
Source: Statistics Explained (https://ec.europa.eu/eurostat/statisticsexplained/) – 17/12/2019.
Stiles, W.A., Styles, D., Chapman, S.P., Esteves, S., Bywater, A., Melville, L., Silkina, A., Lupatsh, I., Grunewald, C.F., Lovitt, R., Chaloner, T., Bull, A., Morris, C., Liewellyn, C.A., 2018. Using microalgae in the circular economy to valorise anaerobic digestate: challenges and opportunities. Bioresour. Technol. 267, 732–742.
Sun, Z., Li, M., Qi, Q., Gao, C., Lin, C.S.K., 2014. Mixed food waste as renewable feedstock in succinic acid fermentation. Appl. Biochem. Biotechnol. 174, 1822–1833.
Taherzadeh, M.J., Karimi, K., 2008. Pretreatment of lignocellulosic wastes to improve ethanol and biogas production: a review. Int. J. Mol. Sci. 9, 1621–1651.
Tang, Z., Yu, G., Liu, D., Xu, D., Shen, Q., 2011. Different analysis techniques for fluorescence excitation-emission matrix spectroscopy to assess compost maturity. Chemosphere 82, 1202–1208.
Tchobanoglous, G., Burton, F.L., Stensel, H.D., 2004. Wastewater Engineering: Treatment and Reuse, fourth ed. McGraw Hill, New York, NY, USA.
Tehrani, S.M., Karbassi, A.R., Ghoddosi, J., Monavvari, S.M., Mirbagheri, S.A., 2009. Prediction of energy consumption and urban air pollution reduction in e-shopping adoption. Int. J. Food. Agri. Environ. 7, 898–903.
Thiriet, P., Bioteau, T., Tremier, A., 2020... Optimization method to construct micro-anaerobic digesters networks for decentralized biowaste treatment in urban and peri-urban areas. J. Clean. Prod. 243, 118478.
Torquati, B., Venanzi, S., Ciani, A., Diotallevi, F., Tamburi, V., 2014. Environmental sustainability and economic benefits of dairy farm biogas energy production: a case study in Umbria. Sustainability. 6, 6696–6713.
Trad, Z., Akimbomi, J., Vial, C., Larroche, C., Taherzadeh, M.J., Fontaine, J.P., 2015. Development of a submerged anaerobic membrane bioreactor for concurrent extraction of volatile fatty acids and biohydrogen production. Bioresour. Technol. 196, 290–300.
Turhal, S., Turanbaev, M., Argun, H., 2019. Hydrogen production from melon and watermelon mixture by dark fermentation. Int. J. Hydrogen. Energy 44, 18811–18817.
Valentino, F., Gottardo, M., Micolucci, F., Pavan, P., Bolzonella, D., Rossetti, S., Majone, M., 2018. Organic fraction of municipal solid waste recovery by conversion into added-value polyhydroxyalkanoates and biogas. ACS Sustain. Chem. Eng. 6, 16375–16385.
Valentino, F., Moretto, G., Gottardo, M., Pavan, P., Bolzonella, D., Majone, M., 2019. Novel routes for urban bio-waste management: a combined acidic fermentation and anaerobic digestion process for platform chemicals and biogas production. J. Clean. Prod. 220, 368–375.
Vinay, K.T., Fdez-Güelfo, L.A., Zhou, Y., Álvarez-Gallego, C.J., Romero, L.I.G., Wun, J.N., 2018. Anaerobic co-digestion of organic fraction of municipal solid waste (OFMSW): progress and challenges. Renew. Sustain Energy Rev. 93, 380–399.
Wachendorf, M., Richter, F., Fricke, T., Graß, R., Neff, R., 2009. Utilization of semi-natural grassland through integrated generation of solid fuel and biogas from biomass. I. Effects of hydrothermal conditioning and mechanical dehydration on mass flows of organic and mineral plant compounds, and nutrient balances. Grass Forage Sci. 64, 132–143.
Wainaina, S., Lukitawesa, Awasthi, M.K., Taherzadeh, M.J., 2019a. Bioengineering of anaerobic digestion for volatile fatty acids, hydrogen or methane production: a critical review. Bioengineered 10, 437–458.
Wainaina, S., Parchami, M., Mahboubi, A., Horváth, I.S., Taherzadeh, M.J., 2019b. Food waste-derived volatile fatty acids platform using an immersed membrane bioreactor. Bioresour. Technol. 274, 329–334.
Wang, J., Wan, W., 2008. Effect of temperature on fermentative hydrogen production by mixed cultures. Int. J. Hydrogen Energy 33, 5392–5397.
Wang, J., Wan, W., 2009. Factors influencing fermentative hydrogen production: a review. Int. J. Hydrogen Energy 34, 799–811.
Wang, K., Li, W., Li, X., Ren, N., 2015. Spatial nitrifications of microbial processes during composting of swine, cow and chicken manure. Sci. Rep. 5.
Wang, W., Xie, L., Chen, J., Luo, G., Zhou, Q., 2011. Biohydrogen and methane production by co-digestion of cassava stillage and excess sludge under thermophilic condition. Bioresour. Technol. 102, 3833–3839.
Waste Management World, 2017. Report: Global Biogas Market to Reach $50 Billion by

2026. https://waste-management-world.com/.
WBA, 2017. https://worldbioenergy.org/uploads/WBA%20GBS%202017_hq.pdf. (Accessed: 17/09/2019).
Wei, Y.M., Li, J.Y., Shi, D.Z., Liu, G.T., Zhao, C.Y., Takayuki, S., 2017. Environmental challenges impeding the composting of biodegradable municipal solid waste: a critical review. Resour. Conserv. Recycle 122, 51–65.
Weiland, P., 2010. Biogas production: current state and perspectives. Appl. Microbiol. Biot. 85, 849–860.
Wongthanate, J., Mongkarothai, K., 2018. Enhanced thermophilic bioenergy production from food waste by a two-stage fermentation process. Int. J. Recycl. Organic Waste Agric. 7, 109–116.
Wu, X., Wei, Y., Zheng, J., Zhao, X., Zhong, W., 2011. The behavior of tetracyclines and their degradation products during swine manure composting. Bioresour. Technol. 102, 5924–5931.
Xiong, Z., Hussain, A., Lee, J., Lee, H.S., 2019. Food waste fermentation in a leach bed reactor: reactor performance, and microbial ecology and dynamics. Bioresour. Technol. 274, 153–161.
Yang, C., He, X.S., Gao, R.T., Xi, B.D., Huang, C.H., Zhang, H., Tan, W., Li, D., 2017. Effect of compositional and structural evolution of size fractionated dissolved organic matter on electron transfer capacity during composting. Chin. J. Anal. Chem. 45, 579–586.
Yang, W., Zhuo, Q., Chen, Q., Chen, Z., 2019. Effect of iron nanoparticles on passivation of cadmium in the pig manure aerobic composting process. Sci. Total Environ. 690, 900–910.
Yentekakis, I.V., Goula, G., 2017. Biogas management: advanced utilization for production of renewable energy and added-value chemicals. Front. Environ. Sci. 5.
Zhang, C., Xiao, G., Peng, L., Su, H., Tan, T., 2013. The anaerobic co-digestion of food waste and cattle manure. Bioresour. Technol. 129, 170–176.
Zhang, F., Chen, Y., Dai, K., Shen, N., Zeng, R.J., 2015. The glucose metabolic distribution in thermophilic (55°C) mixed culture fermentation: a chemostat study. Int. J. Hydrogen Energy 40, 919–926.
Zhang, L., Kai-Chee, L., Zhang, J.X., 2019. Enhanced biogas production from anaerobic digestion of solid organic wastes: current status and prospects. Bioresour. Technol. Rep. 5, 280–296.
Zhao, P., Shen, Y., Ge, S., Chen, Z., Yoshikawa, K., 2014. Clean solid biofuel production from high moisture content waste biomass employing hydrothermal treatment. Appl. Energy 131, 345–367.
Zhen, G., Pan, Y., Lu, X., Li, Y.Y., Zhang, Z., Niu, C., Kumar, G., Kobayashi, T., Zhao, Y., Xu, K., 2019. Anaerobic membrane bioreactor towards biowaste biorefinery and chemical energy harvest: recent progress, membrane fouling and future perspectives. Renew. Sustain. Energy Rev. 115, 109392.
Zhou, A., Guo, Z., Yang, C., Kong, F., Liu, W., Wang, A., 2013a. Volatile fatty acids productivity by anaerobic co-digesting waste activated sludge and corn straw: effect of feedstock proportion. J. Biotechnol. 168, 234–239.
Zhou, H., Meng, A., Long, Y., Li, Q., Zhang, Y., 2014. An overview of characteristics of municipal solid waste fuel in China: physical, chemical composition and heating value. Renew. Sustain. Energy Rev. 36, 107–122.
Zhou, M., Yan, B., Wong, J.W.C., Zhang, Y., 2018. Enhanced volatile fatty acids production from anaerobic fermentation of food waste: a mini-review focusing on acidogenic metabolic pathways. Bioresour. Technol. 248, 68–78.
Zhou, P., Elbeshbishy, E., Nakhla, G., 2013b. Optimization of biological hydrogen production for anaerobic co-digestion of food waste and waste water biosolids. Bioresour. Technol. 130, 710–718.