Chapter 14
Sustainable Recycling and Valorization of Organic Solid Wastes for Fuels and Fertilizers

Lijun Wang, Bahare Salehi, and Bo Zhang

Abstract Recycle and valorization of organic solid wastes can produce fuels, fertilizers and reduce their disposal costs and negative environmental impacts. Municipal solid wastes (MSW) are traditionally dumped in landfills and some MSW components are incinerated to reduce their landfilling volume and recover part of their energy. Composting is widely used to convert biodegradable wastes such as animal manure and food wastes into a compost as a fertilizer. Those traditional technologies have low energy recovery efficiency and low reduction of negative environmental impacts of the wastes due to leachate and emissions generated during those processes. Pyrolysis, gasification, anaerobic digestion (AD) are three advanced technologies with higher recovery efficiencies of energy and materials, and lower environmental emissions that are widely studied to convert organic solid wastes into energy and fertilizer products. However, more studies are needed to improve the economics and environmental impact of those advanced processes by increasing conversion efficiency and the quality of the products, and minimize the negative impacts of hazardous materials in the wastes. Various methods and nanomaterials have been studied to improve the process conversion efficiency and environmental sustainability, and the quality of products for recycling and valorizing various wastes.

Keywords Municipal solid wastes · Agricultural wastes · Circular economy · Environmental sustainability · Anaerobic digestion · Pyrolysis · Gasification · Incineration · Composting

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14.1 Introduction

Global population growth is increasing society's dependence on fossil fuels which causes many environmental issues such as global warming, air and water pollution, and the depletion of these resources. Therefore, there is an increasing demand for sustainable clean energy resources [1]. On the other hand, population growth increases production of industrial, municipal, and agricultural wastes which must be treated and managed due to their associated issues of disposal cost and land use, human and ecological health, and soil, water, and air pollution. Solid wastes can be categorized as biodegradable (bio-wastes) and non-biodegradable wastes [2]. Bio-wastes include manure, crop residues, forest residues, food wastes, and a large portion of municipal solid waste (MSW). The large variation in the physical and chemical properties of solid wastes affects their valorization and profit [2].

Waste management generally follows three principles including (1) identification and evaluation of waste types and quantities, (2) reduction of waste production and (3) reuse and recycle of wastes into value-added products [3]. Waste characteristics such as content of water, biodegradable organic compounds, carbohydrates, and lipids, heating value, particle size, and potential contaminants affect the selection of waste management methods. The water content of wastes plays a key role in the selection of a management approach. Wet wastes such as animal manure are more suitable for biochemical conversion techniques such as anaerobic digestion (AD), composting, and fermentation, whereas the dry wastes are more suitable for thermochemical processes such as incineration, pyrolysis, and gasification. As the water content of wastes can also affect handling and transportation costs, those wastes may have to be treated onsite at a specific scale corresponding to the available amount of the wastes. Furthermore, some technologies can only be used to treat a specific type of wastes. Fermentation and transesterification require wastes with high carbohydrate content and high lipid content, respectively [4]. The main challenges in waste management include minimization of emissions, recovery of fertilizer nutrients, production of high-quality products and closed material recycling loop with free wastes [2]. The wastes can be considered as secondary raw materials to produce industrial products, compared to non-renewable sources [5, 6]. This chapter reviews advantages and disadvantages of waste management technologies in terms of waste reduction, stabilization, material recycling, energy recycling, and GHG reduction. We also discuss methods and nanomaterials that have been studied to improve process conversion efficiency and environmental sustainability, and the quality of products for recycling and valorizing different wastes using three advanced technologies, namely, pyrolysis, gasification, and anaerobic digestion.

14.2 Organic Solid Wastes

MSW and agricultural wastes are two major sources of organic solid wastes that have been used for the production of fuels and fertilizers. It is estimated that global agricultural waste production is more than four and a half times that of MSW. On average, each person around the world generates 3.35 kg of agricultural wastes per day, compared with 0.74 kg of MSW per day. Agricultural wastes are usually managed separately from MSW and a large portion of agricultural wastes are used as inputs for agricultural production activities [7].

14.2.1 Municipal Solid Waste

MSW consists of all organic and non-organic refuses including wet wastes such as kitchen wastes, food wastes, crop straws, garden trimmings and sawdust, and dry wastes such as glass, plastics, metals and ash [8]. Figure 14.1 shows the amounts of MSW generated by region around the world in 2016 [7]. The total annual amount of MSW is estimated to reach 2.2 billion tons globally by 2025 [9]. The quantity and quality of MSW generated depend on the economical, demographic, educational and social status of a region [10, 11]. The United States produced about 258 million tons in 2014 [8, 9]. China collected 191 million tons of MSW in 2015 [12].

The composition of MSW is affected by geographic locations, the areas of collection (such as rural, urban, industrial or commercial areas), seasons, and

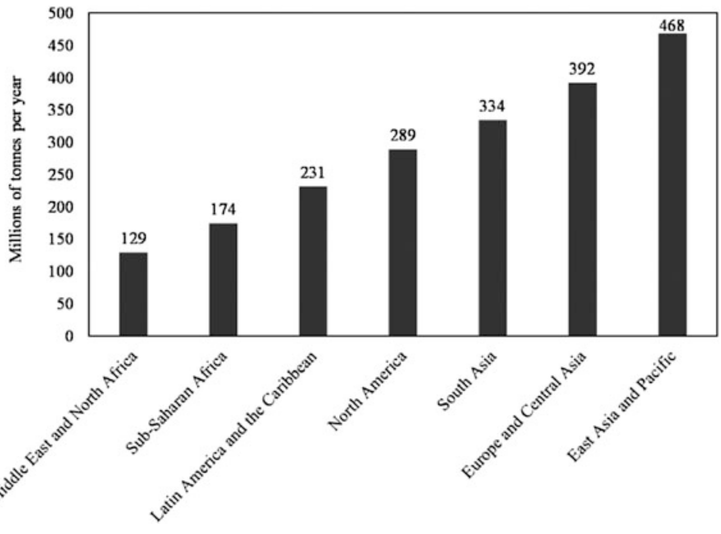

Fig. 14.1 Global municipal solid waste (MSW) generation by region in 2016, reprinted with permission from reference [7]. Copyright @ 2018, The World Bank

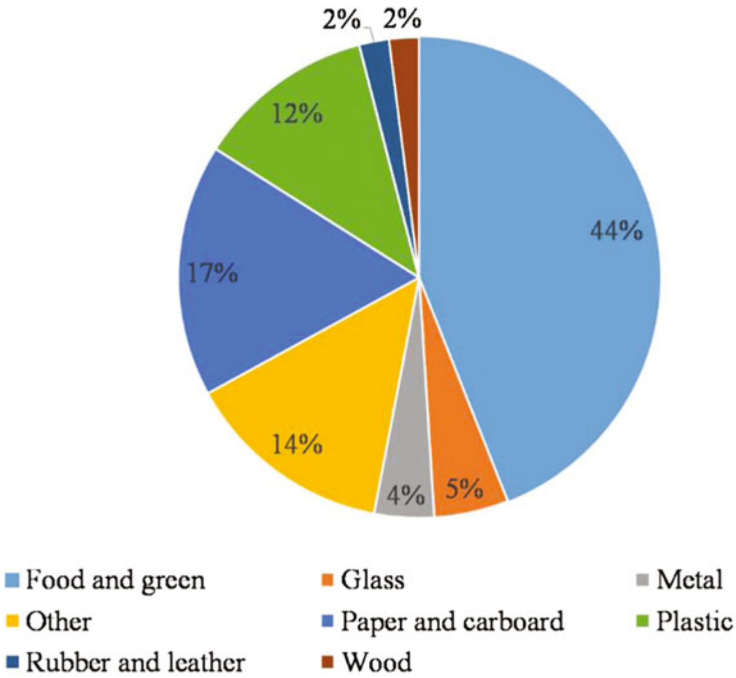

Fig. 14.2 Global municipal solid waste (MSW) composition, reprinted with permission from reference [7]. Copyright @ 2018, The World Bank

recycling levels [13, 14]. Figure 14.2 shows the average composition of MSW around the world. On average, food and green wastes makes up 44% and dry recyclables including plastics, paper, cardboard, metal, and glass are another 38%. MSW around the world contains 70% to 80% organic compounds on average including 44% food and green wastes, 2% wood, 17% paper and cardboard, 12% plastics, and 2% rubber and leather [7]. MSW in China consists of 58.8% food and green waste, 8.5% paper, 12% plastic and rubber, 3.2% fabric and leather, 5% glass, 4.6% metal, 3.9% ceramic, and 7.9% ash. MSW in Europe consists of 32% food and green waste, 29% paper and board, 8% plastics, 11% glass, 5% metals, 2% textile and 13% other materials [8]. MSW in the USA contains 27% paper, 15% food wastes, 14% yard trimmings, 13% plastics, 9% leather, rubber and textiles, 9% metals, 6% wood waste, 4% glass and 3% of other materials [12].

MSW usually contains a large amount of moisture due to the presence of food and yard wastes. Improper management and treatment of MSW may produce large amounts of leachates containing toxic materials likes heavy metals, odors and greenhouse gases causing pollution of soil, water and air [10, 15]. Furthermore, high moisture content and low energy content of MSW result in a low energy recovery rate if the MSW is used as a feedstock in thermochemical conversion processes such as incineration [12]. Large portions of MSW such as food wastes are easily biodegradable and converted to landfill gas (LFG) in a landfill [12]. Besides

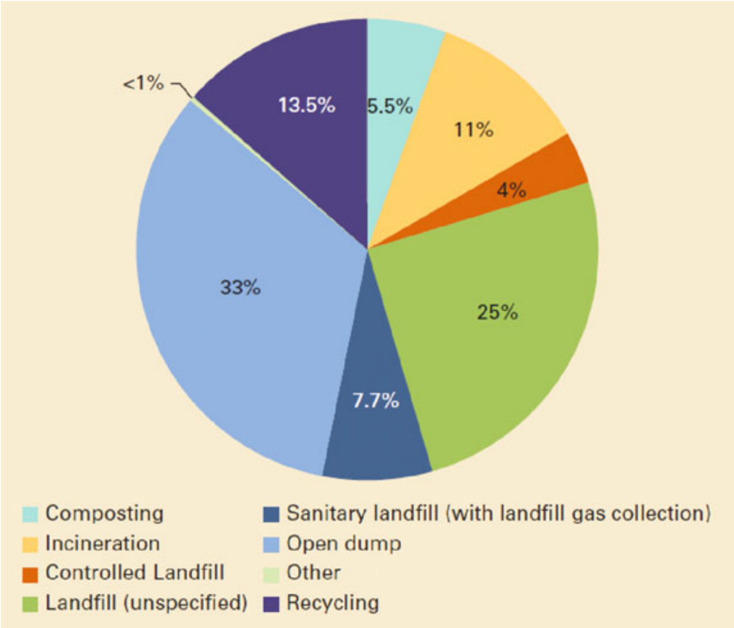

Fig. 14.3 Global municipal solid waste (MSW) treatment and disposal, reprinted with permission from reference [7]. Copyright @ 2018, The World Bank

the negative environmental impact, improper MSW management results in a loss of resources [16]. Appropriate MSW classification and treatment can minimize the negative environmental impact of MSW, but also convert MSW into energy and other value-added products to reduce the use of fossil-based fuels and products. It is recommended to classify raw MSW as an available resource. Different countries have different waste classification methods. Both environmental and economic factors should be considered in the MSW classification [17]. MSW is commonly classified into three groups including i) biodegradable fraction of food waste and green waste, ii) high calorific value components (HCVCs) of plastic, fabric, and paper, and iii) residual fraction of metal, glass, ceramic, and ash. Biological processes such as AD can be used to convert the biodegradable fraction of MSW while the HCVCs can be treated by thermochemical processes such as incineration and pyrolysis to achieve high conversion efficiency [12].

Figure 14.3. shows the current global MSW treatment and disposal methods. Almost 40% of MSW around the world is disposed of in landfills including controlled landfills, sanitary landfills, and other unspecified landfills and another 33% of MSW is dumped in open fields. Only 13.5%, 5.5%, and 11% of MSW undergo recycling, composting, and incineration [7]. Among the 258 million tons of MSW generated in the USA in 2014, 34.6 wt % was recycled and composted, and 12.8 wt % was combusted with energy recovery, and more than 50 wt% was landfilled [8, 9]. A dominant portion or 63.7% of the 191 million tons of MSW collected in

China in 2015 was landfilled, another 34.3% was incinerated, and 2% was treated in biological processes [12].

14.2.2 Agricultural Wastes

Agricultural production has increased more than three times over the last 50 years due to accelerated growth of population. Agriculture produces an average of 23.7 million tons of foods worldwide each day. Agricultural production generates large amounts of organic wastes including animal manure, crop residues, and food processing wastes. Agriculture is responsible for 21% of greenhouse gases emissions [18].

Animal manure. Rapid population growth has increased the demand for animal products [19], which has resulted in the production of large quantities of animal wastes. The estimated amount of animal manure produced in 12 major livestock-producing countries is 9 billion tons each year. In the USA, the amount of manure produced by top three livestock animals, cattle, pigs, and chickens were 1166, 91, and 164 million tons per year, respectively [20]. The amount of manure produced in Canada was estimated at 51 million tons that consisted of 49.181 million tons of water and 2.589 million tons of solid materials including 1.761 million tons of organic matter, 143,000 tons of nitrogen, 46,000 tons of phosphorous, 93,000 tons of potassium, and 545,000 tons of other solids [21]. As shown in Table 14.1 and Table 14.2, there are large variations in quantities and composition for different types of animal manure due to variations in the physiology and anatomy of different animals, body weight, diets, and geographical locations [22, 23].

Animal wastes endanger environment, human health, and animal health due to the potential presence of microbial flora and pathogens. Furthermore, landfilling of those wastes causes gaseous and leachate emissions [19]. The decomposition of organic wastes generates unpleasant odors and releases chemical pollutants into the atmosphere. Moreover, the direct use of extra amounts of animal manure as a fertilizer can accumulate fertilizer nutrients in soil, which leach into surface water and ground-water [19]. However, animal manure can be used to produce value-added products such as (i) fertilizer and soil conditioner, (ii) biofuels and biopower, and (iii) irrigation water [21].

Crop residues. Crop residues are another type of abundant waste from agricultural production. The estimated annual production of crop residues around the world

Table 14.1 Daily feces and urine production for several kinds of livestock. Reprinted with permission from reference [22]. Copyright @ 2018, Elsevier

	Beef cattle	Dairy cows	Fattening pigs	Layers	Broilers
Solid (kg/head/day)	13.28	29.70	1.29	0.132	0.139
Slurry (kg/head/day)	8.52	14.07	2.93	–	–
Total (kg/head/day)	21.80	42.77	4.22	0.132	0.139

Table 14.2 Average elemental composition of fresh manure. Reprinted with permission from reference [23]. Copyright @ 2015, Elsevier

Compositions		Type of manure				
		Pig	Dairy	Beef	Layers	Broiler
Proximate analysis (%)	Moisture content	71.99	75.59	75.66	72.26	63.88
	Volatile matter	66.12	60.60	64.58	62.56	62.47
	Fixed carbon	10.54	11.73	13.73	6.48	10.45
	Ash	24.18	28.20	22.64	32.44	27.76
Ultimate analysis (%)	C	37.74	34.42	37.64	33.02	33.62
	H	5.62	4.91	5.26	4.81	5.06
	O	28.90	30.44	31.90	25.74	30.75
	N	2.79	1.92	2.16	3.39	3.70
	S	0.63	0.65	0.59	0.81	0.89
Mineral element (g/kg)	P	19.86	6.00	6.07	12.83	11.07
	K	15.35	9.39	12.04	23.86	23.35
	Na	2.56	2.29	3.33	3.08	3.90
	Ca	18.44	16.01	12.40	45.17	23.46
	Mg	12.08	8.59	6.54	10.47	7.88
	Fe	3.61	4.04	3.23	2.95	3.68
	Cu	0.66	0.066	0.056	0.082	0.088
	Zn	1.39	0.16	0.13	0.35	0.32

was about 3.8 billion tons in 2011 [24, 25]. About 111 million dry tons of primary crop residues are generated in the USA each year with more than 76% of them being corn stover, and the remaining 24% being wheat and other grains (USDOE, 2011). A number of studies have shown that the sustainable removal rate of crop residues varies between 30% and 70% [26]. The total amount of biomass available for sustainable removal in 25 EU member countries in 2020 was estimated to be 235 million tons including 39 million tons from forestry, 96 million tons from agriculture, and 100 million tons from other wastes [27, 28]. Crop residues are usually burnt or used as animal feed [29]. Crop residues have been considered as an important global renewable resource of biomass for biofuel production [24].

Food processing wastes. It is estimated that more than 50% of food materials, or globally over 1.3 billion tons of foods per year for human consumption, are wasted before and after reaching the customer. Food waste is a complex of lipids, carbohydrates, amino acids, phosphates, vitamins and carbonaceous and can be divided into organic crop residues, catering waste and derivatives including used cooking oils, animal by-products, and mixed domestic food waste. In contrast to other types of waste streams, food wastes undergo biological degradation during handling, resulting in decreased nutrient and energy recovery potential and increased pollutant emissions. Therefore, food wastes are more affected by local conditions and process timing than other types of wastes [30].

Agricultural wastes cause environmental pollution, public health issues, and loss of valuable resources. Sustainable and intensive agricultural production demands sustainable management of agricultural wastes. Animal manure is typically applied to soil as a fertilizer. However, traditional manure management increases global climate change due to emission of methane and nitrous oxides. Runoff of N and P in manure can impair ground and surface water [20]. Innovative conversion technologies for the valorization of agricultural wastes are crucial in the circular economy for transition to sustainable agriculture [31]. Agricultural wastes have been considered as main feedstocks for production of biofuels and biochemicals [32, 33]. AD is an effective technology for converting manure and other wet agricultural wastes to biogas (a gaseous mixture of CH_4 and CO_2) as an alternative to natural gas and digestate as organic fertilizers [34]. Thermochemical technologies of pyrolysis and gasification have been studied to convert dry agricultural wastes into heat, power and biofuels [33, 35].

14.3 Recycle and Valorization of Organic Solid Wastes for Circular Economy and Environmental Sustainability

14.3.1 Circular Economy and Environmental Sustainability Via Recycling and Valorizing Wastes

Conversion of wastes to energy is a typical way to solve two problems at once, reducing fossil fuel consumption and disposing of the wastes [36]. Conversion of waste materials into a wide range of valuable products such as foods, feeds, bioproducts and bioenergy provides both economic and environmental benefits

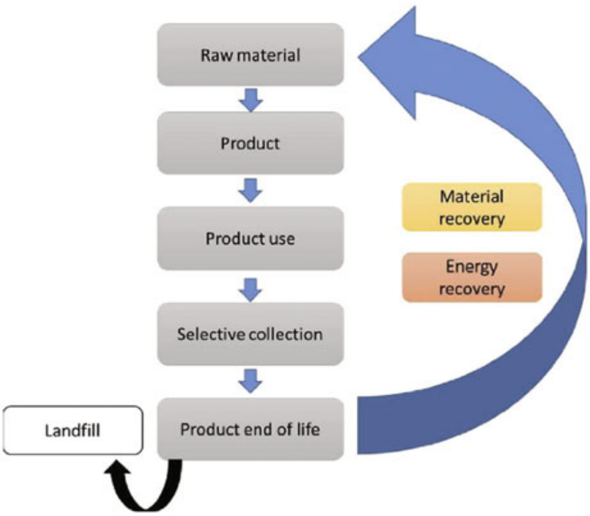

Fig. 14.4 Schematic view of circular economy (CE). Reprinted with permission from reference [5]. Copyright @ 2019, Elsevier

[37, 38]. From the economic viewpoint, it can change the linear economy into a circular economy (CE) by closing the loop of economic value chains as shown in Fig. 14.4, which can save resources and promote environmental sustainability [5].

Reusing or recycling waste materials extends their usability by creating new products in a sustainable manner [5, 39]. It is estimated that the transformation to a circular economy can bring net savings around EUR 600 billion to the manufacturing sector in the EU. Valorization of wastes to energy and products not only decreases the dependency on fossil fuels, but also protects the environment by decreasing GHG emission and consequent climate change, and the land used for the disposal of wastes [36, 37]. Implementation of integrated waste management strategies to reduce the amount of wastes treated by conventional technologies such as landfilling and incineration can significantly reduce their GWP and other negative environmental impacts. Waste management is significantly affected by the technological development, socio-economic and environmental factors. A waste management plan should take into account all environmental, economic and social factors for selecting the most appropriate waste practice in a region. The main criteria for selection of the waste treatment method are long-term sustainability, eco-friendliness, economics and efficiency. In addition, the volume of final residues which still impose an extra burden on the environment and their potential use such as construction materials must be considered [40].

Nitrogen (N), phosphorus (P) and potassium (K) are primary macronutrients that are vital to support plant growth. The increase in world population sharply increased demand for fertilizers that are needed to secure the supply of foods. P and K fertilizers are achieved via mining phosphate rock reservoirs and potash reserves. N fertilizer is chemically produced through a Haber-Bosch process. Although N is considered as a renewable nutrient element in air, the Haber-Bosch process consumes a significant amount of energy for nitrogen fixation, which is around 1–2% of world's total energy consumption [38]. With the current mining rate of phosphorus, P reserves may be exhausted in near future. Potassium is a nutrient element with finite reserves in the earth. Besides recovery of energy from wastes, fertilizer nutrients of N, P, and K can be recovered from the waste streams with significant amounts of N, P, and K such as food wastes, manure, and sewage [5]. There are significant amounts of NPK in organic solid wastes that can be recovered and reused as fertilizers in a sustainable and economic manner. Approximately, 15% and 19% of agricultural nitrogen inputs end up in wastewater and animal manure, respectively, which make them to be good sources for nitrogen recovery. MSW and agricultural wastes contained about 15% and 40% of total mined phosphorus, which make them to be good sources for phosphorus recovery. More than 90% of potassium in agricultural production ends up in animal wastes. These macronutrient elements can be present in the wastes in various forms. For example, P is in the form of free phosphate, polyphosphate, ATP, DNA/RNA and phospholipids. K can be in the form of free potassium ion, while N can be in the form of ammonia/ammonium, nitrate/nitrite, amino acids, DNA/RNA and chlorophyll, respectively [38].

14.3.2 Traditional Technologies for Treatment of Organic Solid Wastes

Landfilling, composting, and incineration are three major commercial technologies for treatment of organic solid wastes. Landfilling and composting are biological processes that decompose organic wastes in the absence and in the presence of air, respectively. Landfilling produces methane-rich landfill gas (LFG), which can be recovered as an energy product. Composting converts biodegradable wastes into a compost as a fertilizer. Incineration is a thermochemical process to burn organic wastes to generate heat and power.

Landfilling. Landfilling is the primary method for MSW management around the world. In Europe, 23% of the MSW was landfilled in 2017 [41]. Figure 14.5 shows a schematic view for landfilling with and without landfill gas (LFG) energy recovery [12]. Landfilling performance is evaluated by LFG collection and oxidation efficiency at the surface of a landfill over time. In a well-controlled sanitary landfill, LFG collection efficiency increases from 40% of the total amount of LFG produced in the first year to around 80% in years 2–25 following initial establishment. Surface oxidation increases from 15% of the LFG produced in years 1–9 to 20% of the LFG produced after 10 years. LFG can be recovered to generate electricity at an energy

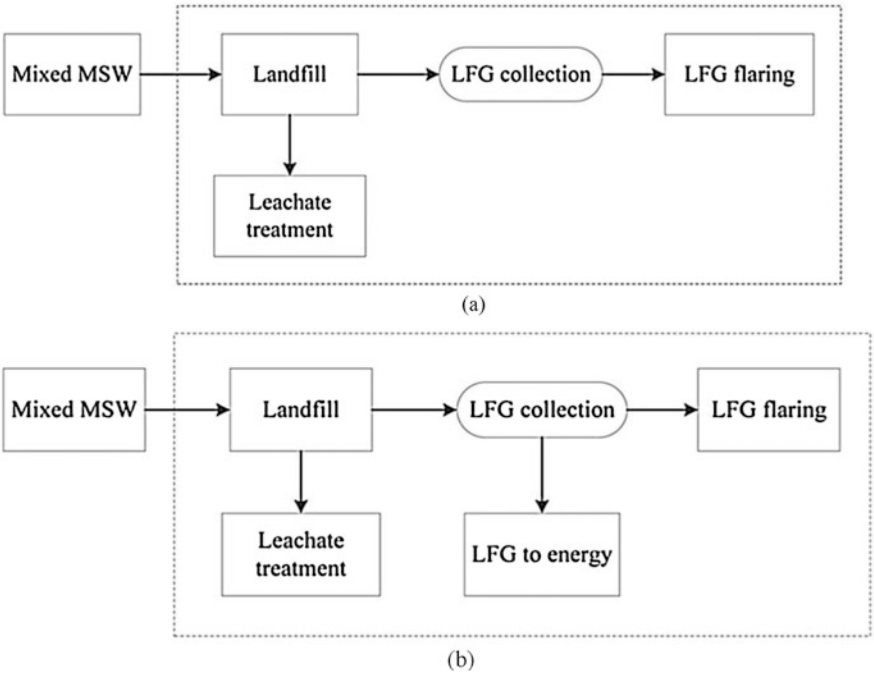

Fig. 14.5 Schematic view of landfilling wastes. Reprinted with permission from reference [12]. Copyright @ 2017, Elsevier

recovery rate up to 30% or 2234 MJ LFG energy per ton of MSW with a higher heating value of 6216 MJ/t. However, the amount of LFG energy that can be recovered from MSW with high content of food wastes and moisture content is significantly lower [12]. Therefore, as LFG collection efficiency is usually low, landfilling is not an efficient approach to reduce the GWP of MSW, particularly for wastes having high moisture content. Operation of a landfill consumes energy. It has been reported that it requires about 66 MJ diesel energy and 54 MJ electricity to treat the leachate from each ton of MSW in a landfill [12].

Incineration. Direct burning or incineration is an ancient method to treat organic solid wastes [42]. Incineration converts dry organic materials into gaseous oxides by exposing them to high-temperatures which produces heat and ash. Incineration is the most widespread waste-to-energy technology used around the world [43]. Half of MSW was incinerated in China in 2020 [12] and an average of 29% of MSW was incinerated in Europe in 2017 [44]. During incineration, almost all organic materials in the wastes are transformed into gaseous oxides such as CO_2 and only a small portion of mineral elements remains in the ash [42]. As the ashes from the incineration of MSW contains heavy metals and dioxins, they are considered as hazardous wastes and are usually disposed of in special landfills [43]. The ash from the incineration of agricultural wastes contains recoverable P and K, which can be used in fertilizers [38]. Incineration can significantly reduce the volume of wastes and destroy any pathogenic organisms. Grate-fired furnaces are widely used to incinerate MSW [43]. For example, it has been reported that incineration of one ton of MSW with an average moisture content of 32.5% produced 20.1 kg of fly ash and 181.6 kg of bottom ash and the overall thermal efficiency of a boiler connected to an incineration furnace was 81.2% [12]. Heat in the flue gas from incineration can be used to dry MSW to further increase the overall energy recovery efficiency [30].

Composting. Composting is an aerobic digestion process to transform organic solid wastes into a compost in the presence of oxygen through oxidation of long-chain organic materials to short-chain products by aerobic microbes, while producing a mixture of gases including CO_2, NH_3 and a small amount of methane [38]. Properly prepared composts normally have 11–14% water content, 90% dry matter, and a C/N ratio of 15–30, which can be affected by the type of feedstocks and composting time. During composting, microorganisms generate heat, which not only promotes physical degradation, but also deactivates plant pathogens and weed seeds present in the wastes. The produced composts have higher pH and lower electrical conductivity than the original wastes due to the removal of volatile organic acids and salts [42]. Aerobic digestion during composting can reduce around 50–75% of the biodegradable compounds in wastes. The generated heat and air injection during composting increase water vaporization and volatilization.

14.3.3 Advanced Technologies for Valorization of Organic Solid Wastes

Both advanced thermochemical processes such as pyrolysis and gasification, and biological processes such as AD have been studied to convert organic solid wastes to fuels and fertilizers. Pyrolysis and gasification, which are alternative thermochemical processes to conventional incineration, can convert organic wastes to chemicals and fuels by reducing the amounts of nitrogen oxides and sulfur oxides emitted to the atmosphere. Furthermore, the solid residue of biochar produced by pyrolysis and gasification is more valuable than the ash from incineration. AD is an alternative biological process for converting biodegradable wastes into biogas as a fuel and digestate as a fertilizer.

Pyrolysis. Pyrolysis is a non-oxidative thermochemical process for decomposing organic materials in the absence of oxygen or in an atmosphere of inert gas at an elevated temperature [8, 38]. Pyrolysis produces three main products: non-condensable syngas, liquid oil, and solid char [38] with yields that depend on the type of feedstock and the operating parameters of temperature, heating rate, and residence time [8, 45, 46]. The main economic advantage of pyrolysis over incineration is that pyrolysis produces high-quality products of oil, syngas and char instead of heat [46]. Pyrolysis is operated at lower temperatures than incineration [8] and is typically conducted at (500 to 550) °C for producing oil as the main product as higher temperatures increase the yield of syngas. In pyrolysis, the residence time varies between few seconds to 2 h. The increase of residence time can increase syngas yield due to tar cracking, and improve the oil quality by reducing its water content and waxy compounds. High heating rates used in flash or fast pyrolysis can increase oil and gas yields and decrease char yield [46]. Pyrolysis is the main approach for producing char with almost all inorganic compounds in the original waste and a considerable fraction of heavy oil compounds dispersed through the solid porous structure. Biochar can be used as a solid fuel, because it has a heating value close to that of coal. Biochar can be upgraded into activated carbon. Biochar contains significant amounts of carbon, nitrogen, phosphorus and potassium, which can be used as fertilizers and soil conditioners by increasing nutrient and water retention in soil, and supporting microorganisms [38].

Gasification. Gasification is the partial oxidation of feedstocks in the presence of an oxidant such as air or pure oxygen at amounts lower than those needed for stoichiometric combustion [47, 48]. Air, pure oxygen, steam and carbon dioxide have been used as gasifying agents that can facilitate the conversion of carbonaceous compounds into gases through endothermic and exothermic reactions [49]. The required heat during gasification can be supplied by oxidation reactions if air or pure oxygen is used as the gasifying agent. However, external supply of heat is required if steam or carbon dioxide is used as the gasifying agent [49]. As shown in Fig. 14.6, gasification can convert the carbonaceous compounds in wastes into the main product of syngas which can be further utilized for power generation or synthesis of various fuels and chemicals [49].

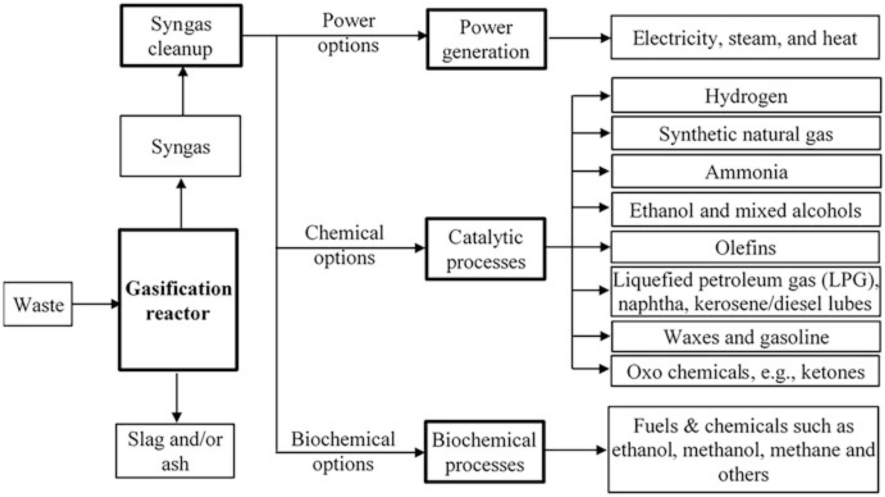

Fig. 14.6 Conversion of waste materials to energy via gasification. Reprinted with permission from reference [49]. Copyright @ 2018, IntechOpen

It has been reported that the electricity efficiency based on gasification is above 27% which is higher than incineration efficiency of 15–20% [9]. Gasification occurs at much higher temperatures (*ca*. 1000 °C) than pyrolysis (*ca*. 500 °C) [48, 50]. During gasification, nitrogen-containing compounds in the wastes are transformed into a volatile phase and inorganic phosphorus and potassium can be recovered from the ash [38]. The main economic benefit of gasification of organic wastes is that it can convert wastes into syngas for on-site electricity and heat generation, and subsequent synthesis of chemicals and fuels [49]. Gasification can also significantly reduce the volume of wastes (up to 90% reduction) to minimize land requirements and costs for waste disposal. Like pyrolysis, gasification can achieve much higher conversion rates and efficiencies than biochemical methods, decompose organic contaminations such as halogenated hydrocarbons, destroy any pathogens, concentrate inorganic elements in ash, and significantly reduce GHG emissions compared with landfilling.

Anaerobic digestion. AD is the degradation of organic materials (Fig. 14.7) by microorganisms in the absence of oxygen for the purpose of producing biogas, which is a mixture of mainly CH_4 and CO_2 as an energy product and digestate residues as a fertilizer product or soil amendment [42, 51]. AD of agricultural wastes can decrease dependency on chemical fertilizers and fossil energy in the agricultural industry [52].

Biogas contains 60–70% methane with the balance being 30–40% carbon dioxide and is the main product of AD. Besides production of biogas, AD can significantly reduce the volume of wastes, transform organic nitrogen-containing compounds into a recoverable form, and produce digestate with concentrated NH_4^+ and K^+ species that can be recovered as fertilizers [38, 47]. The destination of phosphorus in AD is significantly affected by other chemicals such as calcium, magnesium, and iron

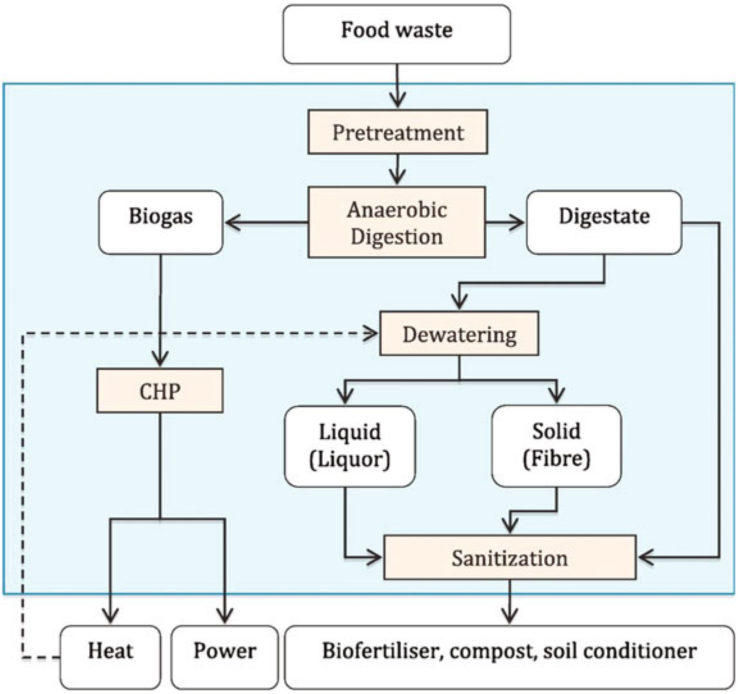

Fig. 14.7 Schematic diagram of anaerobic digestion (AD) process. Reprinted with permission from reference [42]. Copyright @ 2018, Elsevier

which can precipitate phosphorus in the effluent [38]. It has been reported that AD of one ton of waste consumes 50 kWh electricity and that biogas can be used to generate electricity at an overall efficiency of 35%. An increasing number of studies on AD-based biorefineries are being conducted to improve the efficiency of feedstock utilization and nutrient recovery, thus AD is becoming a promising method to recycle organic wastes [37].

14.4 Environmental Impact of Technologies for Recycling and Valorizing Organic Solid Wastes

14.4.1 Life Cycle Assessment of Environmental Sustainability of Wastes Management

Life cycle assessment (LCA) is a widely used tool to assess the environmental impact of the entire use of a product, process or service. LCA includes four steps: scope and goal, inventory data, impact assessment, and interpretation by ISO standards 14,041–14,045. Major environmental indicators for LCA according to the Centrum voor Milieukunde Leiden (CML) method include global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), aquatic depletion, photochemical ozone formation to human health (POFH) [53]. GWP is evaluated by the emissions of methane (CH_4), nitrogen monoxide (N_2O) and carbon dioxide (CO_2). The total GWP can be computed in terms of CO_2 as an equivalent substance. The AP is defined as the acidifying substances in the emissions including SO_2, NO_x and NH_3, which lower soil and water pH. AP can be measured in terms of equivalent SO_2 emissions (kg SO_2 eq). EP is referred to as the increase in the rate of inorganic matter in the ecosystem including NH_3, NO_x and PO_4^{3+} and is mainly measured in terms of PO_4^{3+}[45]. Aquatic depletion is the impact of waste residues on marine and fresh aquatic categories. Vanadium, copper, selenium, nickel, zinc, antimony and metallic substances are the main concerns in aquatic depletion [40]. POFH is caused by NO_x, SO_2, HCl and HF [50]. LCA has been used to compare the environmental impact of technologies used for treating and valorizing organic solid wastes [45, 54–56].

14.4.2 Comparison of Environmental Sustainability of Various Waste Treatment Technologies

Landfilling. One of the environmental issues associated with landfilling of wastes is the leachate. It has been reported that one ton of MSW generates around 500 L of leachate through landfilling which contains 2–4% biological source carbon (BSC). Several approaches have been used to treat leachate, which includes upflow anaerobic sludge blanket (UASB), membrane bioreactor (MBR), nanofiltration, and reverse osmosis. It is estimated that 1.68 kg diesel and 30 kWh electricity are required to treat one ton of typical leachate in a landfill [12]. Furthermore, the high moisture content of MSW reduces LFG collection efficiency, which may cause around 10% of BSC to be released into the atmosphere as methane. Another environmental issue associated with landfilling of MSW is that fossil-based carbon in MSW such as plastics cannot be decomposed in landfills, which thus reduces overall waste reduction efficiency. The environmental impact of landfills are affected by waste composition, LFG treatment and climatic conditions. The GHG emissions for 1 ton of MSW in landfills in Europe was reported to be (124–841) kg CO_2 eq. [41]. Another study showed that net GHG emissions from each ton of MSW in a landfill was 192.2 kg CO_2-eq without LFG recovery, and 116.7 kg CO_2-eq with LFG recovery. The increase of biodegradable waste fraction in MSW increases LFG generation, which increases the GHG emissions [12]. Besides GHG emissions, landfills have environmental impact in factors such as human toxicity, ecotoxicity, terrestrial and aquatic toxicity, eutrophication and land use, all of which must be assessed.

Incineration. During incineration, moisture in MSW is removed and almost all organic compounds are decomposed to a mineralized form (i.e., CO_2) at high-temperatures. For example, during incineration it has been reported that 97.8% of organic compounds can be decomposed and mineralized and 79.2% of inorganic matter is reduced, while the remaining portions of organics and inorganics become fly and bottom ash [12]. The ashes are considered as hazardous waste due to their content of heavy metals and dioxins. Useful metal compounds such as iron and aluminum can be extracted from the ashes that are usually landfilled, but increasing efforts have been made to use the ashes as construction materials after extraction of metals and stabilization of the residual waste [43].

Incineration can significantly reduce and stabilize organic solid wastes while producing heat and power to minimize GHG emissions. Research has shown that incineration of 1 kg of horticulture waste with 40% leaf could recover 4.57 MJ energy in heat and reduce 0.28 kg CO_2 eq emissions from the credit of thermal energy generated [47]. However, energy recovery efficiency from incineration of wastes with a high moisture content is very low [12]. Incineration generates a large amount of flue gas with CO_2 diluted by nitrogen gas from the air used in the process. Compared to the advanced thermochemical conversion technologies of pyrolysis and gasification, incineration has the highest GWP because the flue gas containing CO_2 is directly released into the atmosphere [30]. In general, incineration has higher environmental burden in AP, EP, GWP, human toxicity and aquatic toxicity than pyrolysis or gasification, but less AP and EP than composting and AD [40] [30]. It has been estimated that incineration of one ton of MSW releases 1600 g nitrogen oxide, 42 g sulfur dioxide, 58 g hydrogen chloride, 1 g hydrogen fluoride, 8 g VOCs, 0.05 g cadmium, 0.05 g nickel, 0.005 g arsenic, 0.05 g mercury, 4×10^{-7} g dioxins and furans, 0.0001 g polychlorinated biphenyls and 1 ton carbon dioxide [57]. Furthermore, the environmental impact of the bottom ash generated by incineration should be considered. Studies show that phasing-out incineration could reduce its environmental impact of GWP, AP, EP, POFH and human toxicity cancer if the biodegradable wastes can be separated and treated by a biological process such as AD and composted to mitigate the potential increase in landfill rate [44]. Paper, plastic, and glass in MSW can be recycled as well to mitigate the potential increase in landfill rate.

Pyrolysis. Among the technologies of landfilling, incineration, AD, and pyrolysis for treatment of 1 kg of MSW, pyrolysis has the lowest GWP (1.194 kg CO_2 eq) which is 36.8% of AD, 18% of incineration and 21.8% of landfill values. Furthermore, AP and EP of pyrolysis were only 4.80% and 0.08% of AD, 4.56% and 0.08% of incineration, and 4.79% and 0.07% of landfilling, respectively [45]. The GHG emission of pyrolysis was found to be highly affected by bio-oil yield and a 15% variation of bio-oil yield from baseline values can change GWP from −5.6% to 9.9% [45]. Pyrolysis can decrease the required area for landfilling MSW [45]. The main environmental advantages of pyrolysis over incineration is that pyrolysis generates lower emissions by converting most of the carbon in waste into energy products and char. Pyrolysis of wastes with a high protein content such as food wastes and animal manure releases nitrogen in the three main products, which is desirable in biochar as a fertilizer, but undesirable in bio-oil and syngas as fuels. Furthermore, the application of char from wastes must be evaluated carefully for any significant negative impact on environment and human health, because waste-derived char may contain significant amounts of heavy metals and other hazardous elements depending on the kind of wastes.

Gasification. In comparison with the conventional incineration, gasification provides easier and cheaper control of air pollution by using a limited amount of air or other oxidizing agents to convert organic wastes into syngas mainly CO, CO_2, CH_4, and H_2. Unlike incineration, gasification does not release flue gas into the atmosphere [40]. Gasification using steam, carbon dioxide and metal oxides as oxygen carriers instead of air can avoid the large amount of nitrogen in syngas, which can increase the syngas heating value [49]. The composition of syngas and the emission of gasification are significantly affected by feedstocks and gasification technology as show in Table 14.3 [48].

Gasification of 1 kg of horticulture waste with 40% leaf waste in a downdraft gasifier with 89.7% carbon conversion efficiency recovers 10.2 MJ energy and decreases 1.46 kg CO_2-eq. emissions due to the credits of recovered energy and carbon-neural source of biomass [47]. It has been reported that gasification of wastes had a 28–83% decrease in AP, EP, PPOFH, and NO_x generation, compared with incineration. Furthermore, syngas, which has a much smaller volume than flue gas from incineration of the same amount of wastes, can be purified by removing its acid gases to further reduce the emissions for downstream combustion of syngas [50]. Combustion of syngas from gasification has lower emissions than combustion of bio-oil and char from pyrolysis [50]. Furthermore, syngas from gasification can be used in a gas turbine to generate electricity, which has higher energy recovery efficiency and lower emissions than electricity generated by a steam turbine using heat from incineration [40, 50]. However, gasification of wastes needs to be improved to meet safety and health requirements. The yield and composition of bottom and fly ash are affected by feedstock composition and gasification technology [49]. More attention must be paid to the toxic impact of the bottom and fly ash. It should be noted that both gasification and pyrolysis have high energy demand in the steps of waste pretreatment, syngas cleaning, and endothermic pyrolysis reactions.

Composting. Composting of organic wastes can decrease GHG emissions over that of landfilling, by stabilizing the biodegradable fraction of the wastes and minimizing methane generation [12]. Emissions from composts contain carbon and nitrogen compounds and the amounts of emissions depend on water content, oxygen exposure, C/N ratio, and type of feedstocks. The emissions come from composting treatment and later use as fertilizer. N_2O and CH_4 emissions from composting have significant impact on the overall GWP of composting, while NH_3 emissions contribute to acidification and eutrophication. Moreover, leachate and related emissions from composting can often be assumed to be negligible [30]. Emissions of N_2O, CH_4, and NH_3 in an air-controlled composting plant can be treated by biofilters to minimize their environmental impact. Composting of one ton of waste consumes approximately 15.6 kWh electricity for the composting operation and treatment of leachate and gases. One study shows that the net GHG

Table 14.3 Certified emissions from MSW gasification plants. Adopted with permission from reference [48]. Copyright @ 2012, Elsevier

Company plant		Nippon Steel, Japan	JFE/ Thermoselect, Japan	Ebara TwinRec, Japan	Mitsui R21, Japan	Energos, Norway	Plasco En., Canada
Type of gasifier		Down draft, oxygen enriched air, high temp (1200 °C)	Down draft, oxygen, high temp	Internally circulating fluidized bed, air	Rotary kiln, air, low temp (900 °C)	Moving grate, air, low temperature	Plasma, high temp
Waste capacity (tons/day)		200	300	420	400	100	110
Power production (MW_e)		2.3	8	5.5	8.7	10.2	–
Emissions (mg/m^3 at normal condition)	Particulate	10.1	<3.4	<1	<0.71	0.24	9.1
	HCl	<8.9	8.3	<2	39.9	3.61	2.2
	NO_x	22.3	–	29	59.1	42	107
	SO_x	<15.6	–	<2.9	18.5	19.8	19
	Hg	–	–	<0.005	–	0.0026	0.0001
Dioxins/furans (ng-TEQ/m^3)		0.032	0.018	0.000051	0.0032	0.0008	0.006

reduction by composting was not significant at −32.3 kg CO_2-eq per ton waste composted due to the use of electricity and trace GHGs leakage during composting that contribute to 30.3 kg CO_2-eq and 26.4 kg CO_2-eq for each ton of wastes composted, respectively [12]. It should be noted that GHG emissions of composting depend on waste type and composition (e.g., kitchen organics and garden waste), technology type (e.g., open systems, closed systems, home composting), efficiency of off-gas cleaning at enclosed composting systems, and the use of the compost. It is reported that the overall global warming factor (GWF) for composting varies between significant savings (−900 kg CO_2-eq ton $^{-1}$ wet waste) and a net load (300 kg CO_2-eq ton $^{-1}$) [58]. Material recovery from composting is practical by land application of the compost as a biofertilizer. The use of compost as a fertilizer can recover and recycle fertilizer nutrient from wastes, which can avoid emissions and energy usage for synthetic fertilizer production. The content of nitrogen, phosphorous and potassium in compost affect its value as a fertilizer and depends on N, P, and K content in the wastes. The effect of carbon sink of the compost should also be taken into account as the application of compost as organic fertilizer promotes, over time, a build-up of carbon in the soil which could prove to be a powerful sink for the carbon sequestered in the soil. The potential of carbon sequestration can vary as (133–213) kg $CO_{2_}$eq per ton of mature compost [59].

Compost yield is usually very low, which means that 6–17% of wet wastes, compared with 13–35% of wet waste for digestate yield of AD [30]. Studies show that the net energy recovery rate of composting is only about 9.5% [12]. Another study shows that composting of 1 kg of horticulture waste with 40% leaf could recover 0.28 MJ energy in compost and reduce 0.1 kg CO_2-eq emissions from the credit of compost as a fertilizer [47]. The emissions from carbon and nitrogen compounds in wastes during composting are a great environmental concern about composting in terms of its overall GWP, acidification, and eutrophication if the process is not properly managed. Composting needs a long period of time and the conditions need to be controlled for optimum conversion of wastes into fertilizers [30].

Anaerobic digestion. AD can convert wastes into biogas as an alternative fuel and digestate as an alternative fertilizer. Due to credits given for alternative fuels and fertilizers produced by the technology, AD has a much lower GWP than that of composting, incineration, or gasification. It has been reported that AD of 1 kg of horticulture waste with 40% leaf waste reduces GWP by 1.48 kg CO_2-eq due to the recovery of 8.94 MJ including 7.83 MJ of biogas and 1.11 MJ of digestate-based fertilizer, compared with 0.1 kg CO_2-eq for composting, 0.28 kg $CO_{2\text{-eq.}}$ for incineration, and 1.46 kg $CO_{2\text{-eq.}}$ for gasification [47]. This comparison did not take into account the energy and emissions associated with collection and transportation. In general, AD is more favorable than composting in terms of energy recovery and GWP reduction for biodegradable wastes such as food wastes, animal manure, and crop residues. However, as composting produces less methane than AD by nature, comparison of GHG emissions is usually done without release of methane from AD [47]. There is not a common agreement on the fugitive emissions of methane during AD, which may contribute a significant amount of GHG emissions. However, it has been reported that the amount of methane leakage in AD could be in the range of

0–10% of produced biogas [60]. Another study shows that fugitive emissions of CH_4 are in the range of (0–8) g/kg waste (dry weight) or (0–11) % methane production [30]. GHG emissions from AD can be reduced by increasing the decomposition rate and minimizing GHG leakage during AD [12].

It is common practice to use digestate as a biofertilizer in land applications. However, the low quality and potential environmental risk of the digestate due to the presence of harmful chemicals may limit its direct land application [12]. The value and safety of digestate and compost based fertilizers depend on the quality of wastes. AD and composting are promising methods for the conversion of door-to-door separate organic wastes, and conversion of agricultural residues into fertilizers. Table 14.4 gives the median values of main characteristics, NPK composition, and concentrations of key elements of 12 digestate samples including 6 generated by AD of pig slurry and another 6 generated by AD of cattle slurry [61]. The digestates from AD of animal manure have high fertilizing potential in terms of NH_4-N content, but their land application might be restricted due to their Cu and Zn content, salinity, biogegradability, phytotoxicity, and hygiene characteristics [61].

Summary. Table 14.5 shows a comparison of GHG emissions and environmental impact of solid waste management methods. Environmental impact of waste

Table 14.4 Average characteristics, NPK composition and key element concentration of digestate generated by anaerobic digestion of pig slurry and cattle slurry. Reprinted with permission from reference [61]. Copyright @ 2012, Elsevier

	Digestate from AD of pig slurry	Digestate from AD of cattle slurry
pH	7.91	7.42
Electrical conductivity (dS m^{-1})	25.0	10.9
Dry matter (g L^{-1})	28.9	31.4
Total organic carbon, TOC (g L^{-1})	8.4	13.6
Dissolved organic carbon (g L^{-1})	3.6	6.8
Biochemical oxygen demand (g L^{-1})	4.4	8.3
Total nitrogen, TN (g L^{-1})	3.6	1.7
NH_4-N (g L^{-1})	2.8	0.9
P (g L^{-1})	0.9	0.3
K (g L^{-1})	2.9	1.4
TOC/TN	2.2	9.0
S (mg L^{-1})	384	155
Ca (mg L^{-1})	1345	1293
Mg (mg L^{-1})	499	290
Na (mg L^{-1})	698	525
Cl (mg L^{-1})	1606	558
Fe (mg L^{-1})	103	106
Mn (mg L^{-1})	19.1	10.3
Zn (mg L^{-1})	55.8	14.4
Cu (mg L^{-1})	8.1	6.9
B (mg L^{-1})	2.9	2.6

Table 14.5 Comparison of environmental impacts of various solid waste management methods

Treatment methods	Type of wastes	Main assumptions	GHG emissions (kg CO_2 eq/ton)	Other major environmental impacts	Reference
Landfills	MSW	Energy recovered, waste collection and source separation not included	124–841	• Leachate • LFG emission	[41]
	MSW	No energy recovery, waste collection and transport included	5476		[63]
Incineration	MSW	Energy recovered, waste collection, transport, and residual disposal included	6640	• Hazardous fly and bottom ash • A large amount of flue gas • N_2O, HCl, and SO_2 emissions	[63]
	Horticulture wastes	Energy recovered, waste collection and transport not included, product credits included	−281		[47]
Pyrolysis	MSW	Energy recovered, waste collection, transport, and residual disposal included	1194	• Hazardous fly and bottom ash	[45]
	Corn Stover	Energy recovered, waste collection, transport, and pretreatment included	−864		[64]
Gasification	Horticulture wastes	Energy recovered, waste collection and transport not included, product credits included	−1460	• Hazardous fly and bottom ash	[47]
Composting	Horticulture wastes	Energy recovered, waste collection and transport not included, product credits included	−100	• Low compost yield • High GHGs leakage	
Anaerobic digestion	MSW	Energy recovered, waste collection, transport, and residual disposal included	3245	• Digestate treatment • Methane leakage	[63]
	Horticulture wastes	Energy recovered, waste collection and transport not included, product credits included	−1480		[47]

treatment depends on many factors such as type and composition of the wastes, collection, transportation, local climate conditions, treatment processes, recovery efficiency of energy and materials, and residual waste treatment [62]. There is a large variation in the data of the environmental impact of solid waste management methods reported in the literature due to inconsistencies in the LCA methodology with scope definition and assumptions for the collection of inventory data, impact assessment, and interpretation. In LCA, CO_2 emissions from the conversion of organic solid wastes may come from a biogenic carbon source such as agricultural residues, food wastes, and animal manure or a fossil origin carbon source such as plastics. Biogenic CO_2 emissions are usually treated as carbon neutral (i.e., GWP of zero). Recovered energy and materials are counted as carbon credits with negative carbon emissions [62]. In general, the conversion of MSW that contains fossil carbon sources of plastics usually generates positive GHG emissions due to low energy recovery efficiencies and large amounts of residue that have to be disposed of while conversion of green wastes such as agricultural residues generates negative GHG emissions due to high energy recovery efficiencies, and low amounts of residue requiring disposal. The scope of LCA with and without the consideration of collection, transportation, pretreatment, and residual ash treatment also contributes to significant variations in the assessed environmental impact.

14.5 Challenges and Perspectives of Advanced Waste Conversion Technologies

14.5.1 Pyrolysis of Organic Solid Wastes

Pyrolysis of wastes can reduce corrosion and emissions by retaining alkali and heavy metals, sulfur and chlorine within the products. Pyrolysis operates at much lower temperatures than traditional incineration and can also reduce thermal NO_x formation. Furthermore, as pyrolysis generates a small volume of fuel gas, compared to a large volume of flue gas generated in incineration, it reduces the cost of cleaning emissions. However, Cl and S species such as HCl and SO_2 (or H_2S) may be present in the fuel gas produced by pyrolysis, which have to be removed. Liquid oil and solid char products produced by pyrolysis may contain contaminants such as heavy metals which must be removed [46]. Pyrolysis can be further developed by improving the energy recovery and product quality, reducing emissions, and minimizing the requirement of waste pretreatment [8].

The main challenge for pyrolysis of organic wastes, particularly MSW is in the control of emissions and contamination of products. During pyrolysis, Cl, N and S volatiles are generated at (230–400) °C for HCl, (300–600) °C for SO_2 and above 260 °C for NH_3, which present in gas and liquid products [46]. Mineral elements such as K, S, P, Cl, Ca, Zn, Fe, Cr, Br and Sb present in the pyrolysis oil and fuel gas, which decreases their quality and application. The amounts of those elements in pyrolytic oil and gas depends on temperature and composition of the feedstock [46]. NaCl in wastes reacts with water. Pyrolysis of PVC at high temperatures forms HCl, which presents in the oil and gas products, leading to corrosion of processing facilities. It has been found that the toxicity equivalent (TE) of products from wastes in a rotary kiln was approximately three folds higher than that of the original waste due to the formation of less chlorinated dioxins and furans and polychlorinated dibenzodioxins (PCDD/F). These contaminants limit the applications of the pyrolytic oil. The char produced by the pyrolysis of wastes also has organic and/or inorganic contaminants which limit its applications. Therefore, pyrolysis of wastes should be improved by reducing emissions of HCl, SO_2 and NH_3 in the products, upgrading the quality of the products, and avoiding the use of wastes containing certain components. Several approaches such as gas scrubbing and catalytic conversion can be used to remove HCl, SO_2 and NH_3 in the pyrolytic products [46].

More studies are needed to improve the quality of pyrolytic products and reduce environmental pollution during the pyrolysis of organic wastes. There is a large variation in pyrolysis characteristics among the wastes. Pretreatment and separation of wastes are effective ways to control undesirable elements in the pyrolytic products [65]. Dehalogenation of plastic wastes can remove halogens prior to pyrolysis to prevent formation of HCl in oil and gas products. Separation of wastes is also an effective way to prevent contaminants from entering oil and gas products. Pyrolysis of food wastes in MSW leads to the formation of higher concentrations of Cl and S in pyrolytic oil, and low heat value due to the high moisture content of food wastes. Food wastes can be separated from MSW and processed using other methods such as composting and AD. Pyrolysis can also be combined with gasification or combustion methods to reduce overall contaminants [46]. Removal of nitrogen compounds in protein-rich wastes prior to pyrolysis can reduce the nitrogen content in the pyrolytic oil [65].

Pyrolysis of organic solid wastes affords bio-crude oil, which is considered as a promising alternative to petroleum for the production of transportation fuels and other valuable chemicals [66]. The pyrolytic oil can be catalytically upgraded using catalysts containing iron (Fe^-) and calcium (Ca^-) that have good performance in bromine and chlorine removal, respectively. Although the bio-oil usually has a lower sulfur content and thus fewer emissions of SO_2 than conventional fuels, it has some undesired properties, such as the high oxygen content due to oxygenated compounds (ketones, phenols, aldehydes, esters), high viscosity, and high corrosiveness. Therefore, it is necessary to upgrade the bio-oil into transportation fuel. Upgrading of bio-oil can be carried out through emulsification, esterification, catalytic cracking, solvent extraction, or hydro-deoxygenation [67, 68].

14.5.2 Gasification of Organic Solid Wastes

Gasification has been investigated to convert organic solid wastes into syngas for heat and power generation, synthesis of liquid fuels, and production of hydrogen.

Significant advances have been made in gasification technology and syngas utilization [69]. However, more research is needed to address several critical issues in gasification including ash agglomeration, syngas quality control and cleaning, and efficient syngas utilization [69]. The toxic and explosive nature of syngas increases safety concerns and necessitates reliable control equipment. Moreover, two-step conversion of organic solid wastes into energy products via gasification of the solid wastes into syngas and downstream utilization requires a complex plant with strict operational and maintainence schedules. Conditioning and cleaning syngas for downstream utilization is costly [48]. One of the main obstacles in gasification of organic wastes is instable operation due to the heterogeneity of wastes with large variation in composition, especially MSW, which requires pretreatment of the wastes prior to gasification. Furthermore, although a gas turbine has higher energy efficiencies and lower emissions than a steam turbine to generate electricity from the syngas produced by gasification, syngas from gasification of organic solid wastes cannot meet the quality requirements of a gas turbine. The main potential areas which need to be developed for gasification of organic solid wastes include (1) increasing the gasification efficiency, (2) using selected waste streams, and (3) syngas cleaning and upgrading to be used for synthesis of liquid fuels and chemicals [50].

A chemical looping gasification (CLG) process uses lattice oxygen in an oxygen carrier such as metal oxides as an oxidant agent to avoid direct contact between fuel and air [70]. CLG can increase gasification efficiency, avoid introduction of a large amount of nitrogen in air into syngas, and reduce tar and carbon dioxide in the syngas [71]. A CLG process is usually implemented as dual fluidized bed reactors to ensure high rates of heat and mass transfer via fluidization. An oxygen carrier is used as the bed material of the gasification reactor to supply oxygen and heat. The reduced oxygen carrier is then transported into the second reactor where it is oxidized with air for re-use. The overall reaction of both reactors using an oxygen carrier is exothermic that is the same as biomass gasification with pure oxygen. It has been reported that CLG of biomass with natural hematite as an oxygen carrier increases carbon conversion and gas yields by 7.45% and 11.02%, respectively, while decreasing tar content by 51.53% compared with steam gasification [72]. A number of Ni, Co, Cu and Fe-based materials have been tested as oxygen carriers. Pure metal oxides often do not satisfy all the favorable traits of an oxygen carrier and the reaction rates of pure metal oxides are reduced greatly after a few reduction and oxidation cycles [73]. Bimetallic oxygen carriers and metal oxides on novel porous supports have been studied to enhance the performance of CLG [71, 74]. Chemical looping processes with an oxygen carrier of metal oxides can be used to combust organic solid wastes and syngas, or gasify organic solid wastes [75–77]. Some metal oxides such as CaO, MgO, and BaO can be used not only as an oxygen carrier to supply oxygen for completely or partially oxides organic solid wastes, but also an adsorbent to remove H_2S, HCl, and CO_2 from the product gas [76, 78, 79].

14.5.3 Anaerobic Digestion of Organic Solid Wastes

AD produces biogas as a renewable energy product from various biodegradable wastes at different yields [80]. Biodegradability of organic wastes in AD depends on the complexity and accessibility of the organic materials, and their physical properties including particle size and porosity. Biodegradability of organic wastes can be assessed by biochemical methane potential test (BMP) [51]. Various physical, chemical and biological pretreatment methods have been studied to improve the digestibility of agricultural wastes, particularly lignocellulosic crop residues [81]. Co-digestion of manure and crop residues can increase biogas production by providing a feedstock with an optimum C/N ratio. Anaerobic co-digestion of manure and pretreated crop residues significantly increases biomethane production [82]. One of the main challenges in AD of organic solid wastes is reducing emissions of methane, carbon dioxide, ammonia and other odorous gases to the atmosphere, because this results in greenhouse gas and contributes to air pollution, and lowers the energy value of the wastes [42].

Nanomaterials have been studied as additives to improve the performance of AD, which can be classified into four categories: nanoscale zero valent metals (NZVMs) (e.g. Fe, Ni, Cu, Co, Ag, Au), metal oxide NPs (e.g. ZnO, CuO, TiO_2, MgO, NiO, Fe_2O_3), carbon based nanomaterials (e.g. graphene, diamond, nanotube and nanofibers), and multi-compound NPs [80, 83]. Nanomaterials with nano-sized structures and specific physicochemical properties can have positive and negative effects on the rate of AD through interaction with feedstock and microorganisms [83]. Studies have shown that ZnO, CuO, Mn_2O_3 and Al_2O_3 significantly reduce biogas production rate that can be attributed to the toxicity of these materials. The impact of TiO_2 and CeO_2 is completely dependent on their concentrations in the reactor and digestion time. Nano-iron oxide (Fe_3O_4) has a remarkable positive impact that can increase methane production by 234% due to the presence of non-toxic Fe^{3+} and Fe^{2+} ions. It has also been reported that addition of nano zero-valent iron (NZVI) results in a mixed effect on methane production depending on its concentration. The addition of silver or gold nanoparticles result in either a decrease or no change in biogas production rate, depending on their concentration in the reactor. Addition of micro/nano fly ash and micro/nano bottom ash has a positive impact and considerably increases biogas production, but the addition of fullerene (C60) and silica (SiO_2) nanoparticles, and single-walled carbon nanotubes had no effect on cumulative biogas production. The ZnFe nanocomposite can significantly improve methane production by up to 185%. Moreover, ZnFe with 10% carbon nanotubes (ZFCNTs) and zinc ferrite with 10% C76 fullerene (ZFC76) showed a positive effect on hydraulic retention time and enhanced methane production up to 162% and 146%, respectively [80].

Since the AD digestate is used as a fertilizer, the nutrient recovery becomes significant which can be improved by decreasing nitrogen emission and increasing the conversion of polyphosphate to orthophosphate. The digestate is usually composted prior to its land application. The loss of nitrogen to the atmosphere can be controlled by properly designing the composting process and adjusting operating conditions such as aeration mode and rate, water content, porosity, and temperature. Decrease of the anoxic or anaerobic microenvironment and the water content can lower denitrification and consequently NO_2 emissions, and increase the N recovery potential [38].

Another challenge of AD is that it is still not common for widespread land application of composting and digestate as biofertilizer because of its low quality and environmental risk. Some countries restrict direct use of the digestate as fertilizer due to concerns on its quality and safety [12]. The chemical composition of the digestate is highly dependent on the feedstock composition. The digestate usually has higher concentrations of nitrate, ammonia, Ca and Mg than the original wastes. The quality of digestate can be improved by optimizing the AD process and pretreatment of the organic wastes. AD generates a large amount of liquid effluent with dissolved N, P, and K fertilizer compounds. Instead of direct land application of the digestate, the solid digestate can be converted into biochar that can be used to recover fertilizer nutrients in the digestion effluent to produce high-quality fertilizer and recycle the water [68, 84].

14.5.4 Perspectives of Advanced Organic Solid Wastes conversion Technologies

Advanced thermochemical conversion technologies, pyrolysis and gasification, have been studied as environmentally-friendly alternatives to traditional incineration for the recovery of energy from organic solid wastes. AD has been studied as an alternative to composting to recover both energy and fertilizer nutrients from organic solid wastes. However, selection of a waste conversion technology should consider the type of wastes, the process efficiency, and the desirable products. Table 14.6 summarizes the challenges and recommendations of advanced conversion technologies for the valorization of various organic solid wastes. In general, thermochemical processes of pyrolysis and gasification can be applied to convert dry biomass wastes, waste plastics, waste paper, and cardboard into petroleum-like oil, syngas, and char as main products. Thermochemical conversion of organic wastes faces challenges of high HCl, NH_3, and SO_2 emissions due to the presence of Cl, N and S containing compounds in the wastes, ash agglomeration due to the use of high temperatures, quality control of char, oil, and syngas products, and safety control of the explosive and toxic syngas products. More studies on pretreatment and separation of wastes, catalytic upgrading of products, and novel process development are needed for the commercialization of pyrolysis and gasification technologies to valorize organic solid wastes. The biological process of AD can be applied to convert wet biogenic wastes of agricultural residues, animal wastes, food wastes, and yard waste into biogas and fertilizers as main products. Biogenic waste usually has high moisture content and is more suitable for AD than for thermochemical

Table 14.6 Challenges and recommendations for the valorization of organic solid wastes with advanced conversion technologies

Processes	Type of wastes	Challenges	Recommendations	Reference
Pyrolysis / gasification	• Dry agricultural /forestry residues • Waste plastics • Waste paper and cardboards	• HCl emissions from polyvinyl chloride (PVC) in MSW • NH_3 emissions from protein-containing wastes • SO_2, and • Ash agglomeration • Product quality control • Syngas safety control	• Pretreatment and separation of cl, S and N containing compounds • Catalytic conversion and upgrading products • Syngas cleaning and upgrading • Novel gasification technology	[46, 50, 65, 78]
Anaerobic digestion	• Wet agricultural residues • Animal wastes • Food wastes • Yard waste	• Low biodegradability • Undesirable C/N ratio in the wastes • Large amounts of digestate and effluent	• Pretreatment to increase digestibility • Co-digestion to adjust C/N ratio • Application of nanomaterials and additives for enhanced efficiency • Value-added processing of digestate and effluent	[81, 84]

conversion. However, AD faces the technical barriers of low digestibility, unbalanced C/N ratio in the wastes, and generation of large amounts of solid digestate and effluent. Therefore, studies are needed to increase the digestibility of wastes via pretreatment, co-digestion, and biologically active additives, and for processing digestate and effluent.

Thermochemical conversion and AD can be used to efficiently convert different types of organic solid wastes, therefore, it is critical to separate and sort those wastes. In this case, the inorganic wastes of metals, glass, ceramic and ash should be removed from the organic solid wastes prior to conversion. Dry non-biodegradable wastes of plastic, rubber, fabric and leather can be converted by pyrolysis or gasification, while wet green biogenic wastes of food and yard wastes, agricultural residues, and animal wastes can be converted by AD. Dry biogenic wastes such as paper, cardboard, agricultural and forestry residues can also be converted by pyrolysis and gasification.

14.6 Conclusions and Future Outlook

This chapter has evaluated the advantages and disadvantages of waste management technologies in terms of waste reduction, stabilization, material recycling, energy recycling, GHG reduction, and other environmental factors. Feedstock composition and technical conditions used in those technologies can affect efficiency, economics and environmental sustainability of each technique, and portfolio and quality of products. Landfilling, incineration, and composting are three traditional commercialized methods for treatment of organic wastes. Conversion of waste materials into a wide range of valuable products provides both economic and environmental benefits. Both advanced thermochemical processes such as pyrolysis and gasification, and biological processes such as anaerobic digestion have been studied to convert organic solid wastes to value-added products such as fuels and fertilizers. Although thermochemical methods including incineration, pyrolysis, and gasification have faster conversion rates and higher waste reduction efficiencies than biochemical methods of composting and anaerobic digestion, the exhaust gas cleanup needs to be improved to meet safety and health requirements. Pretreatment and separation of wastes are effective ways to control undesirable elements in the products produced by thermochemical conversion technologies. On the other hand, biochemical approaches, specifically anaerobic digestion, have better nutrient recovery and can remarkably reduce emissions and energy usage for producing biogas as an energy product and digestate as a nutrient rich co-product of fertilizers. However, anaerobic digestion needs to be improved by removing some hazardous materials from the wastes, increasing biogas production efficiency, and enriching nutrient content. Nanomaterials have been studied to improve conversion efficiency and quality of products for recycling and valorizing organic wastes and are possibly practical for land application of the digestate and compost as a biofertilizer. However, low quality and potential environmental risk of the digestate and compost due to the presence of harmful chemicals may limit its direct land application. Value and safety of digestate and compost based fertilizers depend on the quality of wastes. Anaerobic digestion and composting could be promising methods for conversion of selected organic wastes such as food processing wastes and agricultural residues into fertilizers. Digestates from anaerobic digestion of animal manure have high fertilizing potential in terms of NH_4-N content but their land application might be restricted by their Cu and Zn content, salinity, biogegradability, phytotoxicity, and hygiene characteristics.

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