CHAPTER

14

Valorization of municipal solid waste in biorefineries for the creation of a circular economy: role of emerging technologies

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1. Introduction

Municipal Solid Waste (MSW) is defined as the waste generated within municipalities by households, schools, offices, and businesses [1]. Worldwide, close to 2 billion tons per year is currently produced with a projected increase to 9.5 billion by 2050 [2]. The content of plastics (used for packaging, construction, transportation, in healthcare and electronics) in MSW is highest in the developing countries [3]. With the steady increase in urban population and consumption, MSW generation volumes are also growing to more than 1.3 billion tons worldwide yearly [4]. MSW generation is expected to increase to 2.2 billion tons yearly by 2025 (46% organic content) [4]. The data for MSW volume generated is impressive. For example, every year, the European Union alone generates enough MSW to cover the island of Malta (316 km^2) with a layer of MSW almost 2 m high! [5]. In developed nations, most of the MSW wastes is landfilled or incinerated. In developing nations, MSW is often dumped on specific areas of land without any means to protect the environment or composted in open piles without any ways to control the processes [6]. Today, in many regions of the world, there is a shortage of available space for waste disposal [2]. The development of novel

Current Developments in Biotechnology and Bioengineering
https://doi.org/10.1016/B978-0-444-64309-4.00014-3

strategies for MSW management, processing, and disposal is critical for mitigating its adverse effects on the environment and human health.

Currently, government attention is focused on strategies for reducing the amount of MSW heading to landfills and incineration units. The U.S. Environmental Protection Agency (EPA) recommends the following three actions: (1) source reduction, (2) recycling, and (3) composting [7]. In the United States, much of recent technological effort has been devoted to the composting of MSW organic fractions (mainly yard and food wastes). European Union waste management hierarchy consists of five strategic options: (1) prevention, (2) reuse, (3) recycling (4) other forms of recovery (e.g., energy recovery), and (5) disposal (e.g., landfill) [2]. Plastics are often recovered and shipped to China for further processing. However, the recent reduction in China's appetite for the MSW plastic fractions has created new pressures in the United States for the development of more sustainable technologies for the processing of this fraction. There is also a growing body of literature on the processing of organics via anaerobic digestion. Fig. 14.1 shows the current paradigm of MSW utilization [8]. This paradigm is based on the use of four main conversion technologies (landfill, incineration, compost, and anaerobic digestion). However, in Europe, while landfilling significantly decreased by 54% (from 288 to 131 kg/capita) in the last 15 years, incineration increased by 60%, recycling by 59%, and composting and anaerobic digestion by 53% [2].

Several new technologies are being developed worldwide for the processing of MSW fractions. In general, these technologies can be divided into two categories: those for the processing of wet materials and those used for the processing of dry materials. Fig. 14.2 shows the classification of conversion technologies depending on the moisture content of the material processed.

These emerging technologies can be integrated to create biorefineries. Analogous to a petroleum refinery, a biorefinery is a complex processing system that integrates conversion processes and various equipment to convert organic waste streams into fuels, power, and useful chemicals [9]. The creation of MSW biorefineries is an important component to create a circular economy, as MSW biorefineries are a proposed and possible solution to decreasing

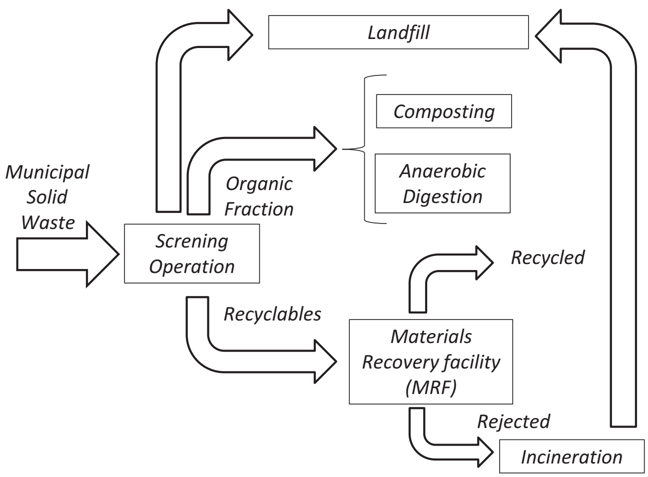


FIGURE 14.1 Conventional pathway for MSW processing.

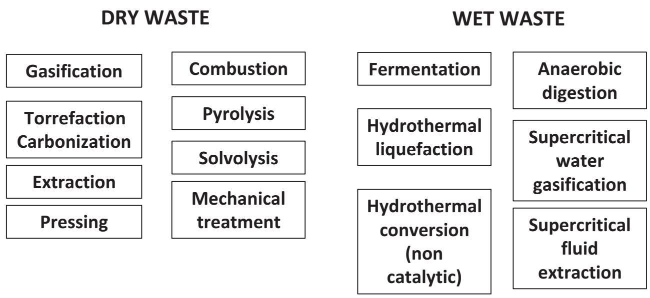


FIGURE 14.2 Conversion technologies depending on the moisture content of the biomass processed.

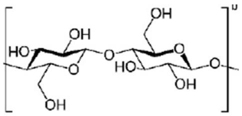
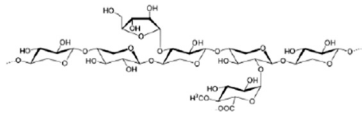
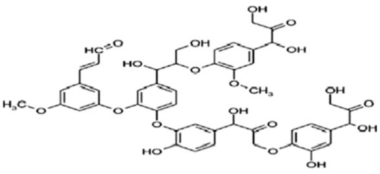
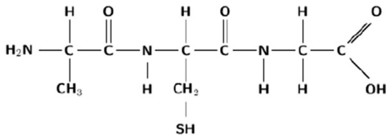
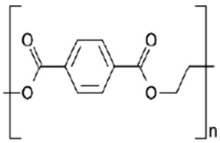
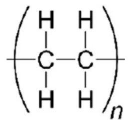
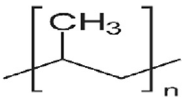
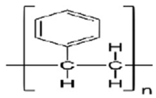
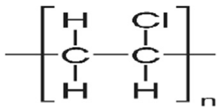
natural resources, preservation of current resources, and the need to close the carbon loop. In our current economic model, also called the *linear economy*, we "take, produce, consume, and dispose." In a circular economy, what was considered waste is turned into a resource, maintained for as long as possible in a closed loop [5]. The overall new philosophy is to not waste the waste, but to use the waste as raw materials to create new products or fuels. Our chapter is a review of existing MSW management practices and of biorefinery concepts to create a circular economy.

2. Composition of MSW

MSW is a heterogeneous material that is difficult to sample and characterize [1,10]. It contains fractions of newspaper, wood, yard trimmings, food waste, paper, and paper board [10]. Its overall composition and production rate vary from country to country [11]. Food waste is the main fraction in most countries (Jordan: 63 wt.%, Malaysia: 36−60 wt.%, Denmark: 46 wt.%, China: 57 wt.%). Anaerobic digestion, composting, and landfilling are the main technologies used for dealing with food wastes. Landfilling today, manages more than 95% of food waste [2]. Plastic (10−31 wt.%), and paper (8−21 wt.%), often used for packaging, are the second most important fractions. Textiles and wood/gardening wastes can also be found in significant quantities (1−10 and 0.3−10 wt.% respectively). The inorganic fractions (metals, glass, aluminum) typically account for between 2 and 9 wt.% [10−17]. Food wastes, paper, paper boards, and wood gardening are most often called the *organic fraction of municipal solid wastes* (OFMSW). Plastics contribute most of the calorific value of MSWs (Polyethylene: 46.3 MJ/kg, Polypropylene: 46.4 MJ/kg, Polystyrene: 41.4 MJ/kg) [18]. Because of the high moisture content, the high heating value of MSWs is typically between 5 and 20 MJ/kg [11,16]. Microbial contamination of MSWs is a common issue due to high moisture content [2]. An energy-intensive drying step is often recommended before transportation [2]. The main polymeric materials found in MSWs can be classified as biopolymers (natural or synthetic from biomolecules) and synthetic polymers (mostly derived from petroleum) (See Table 14.1).

The main biopolymers present in MSWs are cellulose, hemicellulose, lignin, and proteins. All biopolymers are composed of carbon, hydrogen, and oxygen. Only proteins contain nitrogen and sulfur. The main synthetic plastics are Polyethylene terephthalate (PET) (9 wt.%), Polyethylene (PE) (50 wt.%), Polypropylene (PP: 12 wt.%), Polystyrene (PS: 8 wt.%), and

TABLE 14.1 Main Molecules found in the organic fraction of MSW.

Biopolymers	
Cellulose	Hemicellulose
	
Lignin	Proteins
	
Synthetic polymers	
Polyethylene terephthalate (PET)	Polyethylene (PE)
	
Polypropylene (PP)	Polystyrene (PS)
	
Polyvinyl chloride (PVC)	
	

Polyvinyl chloride (PVC: 15 wt.%). Thermoplastics represent 80% of the plastics consumed. The plastics found in MSW come from parts of bags, sacks, wraps, soft drinks, milk, and water containers [17]. Depending on the level of branching and density, PE can be classified as high-density polyethylene (HDPE) 20 wt.% and low-density polyethylene (LDPE) 30 wt.%. Branched PE has relatively lower densities [18]. Six types of plastic fractions can be separated by advanced sorting facilities: (1) Low-density polyethylene (LDPE) film, (2) high-density polyethylene (HDPE), (3) polyethylene terephthalate (PET), (4) PP, (5) mixed plastic (made or two to three different fractions of plastic), and (6) others.

TABLE 14.2 Chemical, Elemental and compositional analysis of organic fraction of MSW (OFMSW).

Chemical-composition		Elemental composition		Compositional analysis	
Total solid (T.S) (%)	15–50.2	S (%)	0.1–0.9	Lignin (% of VS)	3.8–18.5
Volatile solid (V.S) (%)	7.4–36.1	H (%)	5.6–7.3	Carbohydrates	35–63.2
CH_4 (NL/kg.VS)	177–580	C (%)	37.6–51.3		
Total kjeldahl nitrogen (TKN) (g/kg)	1–28	N (%)	1.5–3.8		
Chemical oxygen demand (COD) (g/kg)	140–575				
Total phosphorous (TP) (g/kg)	0.5–13				

Synthetic polymers are mostly composed of carbon and hydrogen. 60% of the PE (LDPE (35%) and HDPE (25%) is recovered in our current systems) [18]. PET contains relatively large quantities of oxygen. While C, H, and O are not major challenges for the processing of MSWs, fractions containing N and S result in the formation of pollutants when processed by thermochemical conversion technologies. Processing materials with Cl is a major challenge for both biochemical and thermochemical rounds. An important parameter for most biological conversion processes (anaerobic digestion (AD), composting) is the C/N ratio. This parameter is often higher than 100 for yard waste and lower than 20 for food wastes [19]. For AD, the C/N ratio of the feedstock needs to be in the range of 25–30. For composting, it should be between 30 and 35 [20]. Although the current thermochemical conversion technologies generally process wastes with low N content better, the presence of N in the feedstock could be very beneficial if carbons with a high content of nitrogen are the targeted product [21].

Source separation of MSW is critical for waste diversification. It allows for the use of a broader spectrum of conversion technologies and for the production of a residue, which can be used as a fertilizer [13–15]. Depending on how the MSW is collected, it can be classified into three types: Source separated MSW (SS-MSW), separately collected organic fraction MSW (SC-OFMSW), and source sorted organic fraction of FMSW (SS-OFMSW). The composition of the OFMSW has been presented in Table 14.2.

3. Sustainability and business models

At the Johannesburg Summit, Kofi Annan discussed the intellectual limitations of extreme schools of thought regarding economic development and the environment [22]. In one extreme, a group proclaimed that it is impossible to have economic growth without harming the environment. The second group defended the idea that it should be socially unacceptable to have economic growth if it harmed the environment. Dr. Annan recommended to look beyond these two paradigms and to find ways to live in harmony with the environment while creating economic opportunities via a circular economy. It is certainly possible to find synergisms between economic growth and environmental protection [22].

Overall, from 2000 to 2014, there has been a decrease in MSW generation (from 523 to 475 kg/capita). In 2014, Europe generated 475 kg MSW/capita [2]. The production of MSW varies widely from higher waste producers, such as Denmark and Cyprus (759 and 626 kg/capita respectively) and low producers Poland and Rumania (272 kg/capita) [2]. The European Commission adopted in 2015, its plan for a circular economy to reduce the amount of plastic waste in circulation. This plan involves enhancing plastics reuse and design for recyclability [3]. North European countries are developing new policies and business models [3]. For example, in Sweden, every producer of plastic packaging is now obligated to ensure that the waste is collected, recycled, recovered, or disposed of [3]. Plastics producers are now responsible for the collection, recycling, and disposal of plastic wastes. This model is very important because it encourages producers to develop recyclable products free of hazardous substances. Today, in Sweden, there is an 80% minimum content of recyclable plastics in packages. Packaging fees paid by companies that produce plastic packaging is now financing the collection and recycling of plastic wastes. Packaging producers are cooperating with waste collection companies, while some have created their own collection and recycling operations. Overall, in Sweden, recycling and incineration of MSW account for close to 50%, and only 1% goes to landfills [2]. This is a result of the progressive landfill policy tax imposed in 2000 and a 2002-ban on landfilling sorted combustible waste. This ban was expanded in 2005 to include all organic wastes [2].

Costa Rica has launched a private-public program called *ecolones* to promote recycling (https://ecolonescr.com/). The program is simple; after separating and cleaning the recyclable streams (plastic, glass, tetra pak, aluminum cans, and tune) the members of the program bring them to the nearest collection center where they receive in exchange "ecolones," a virtual currency that can be accumulated and exchanged for products in participating companies. The case of Kenya shows how far the political will can go to reduce the use of plastic bags, the enforcement of the world toughest plastic bag ban. Kenyans, using plastic bags in their businesses risk up to 4 years imprisonment or fines close to $ 40,000.

Innovative business models are also being implemented in the textile and biodiesel industry. Concepts like Total Oil Management are revolutionizing the way resources are being used. In Total Oil Management, the handling of the entire oil process, ordering, delivering of fresh cooking oil, storing, handling, and recycling of used cooking oil is performed by the same company. The customers only pay a fee for the use of the oil. The textile industry, meanwhile, has also been very creative in its recycling used clothes. Thrift stores are, of course, the first option that comes to our mind. Other savvy methods have also been employed, like the shipment of used clothes to poor regions in Africa or South America or to the mountainous regions of Asia where there is a need for cheap warm clothes. Upcycling into new designs is also becoming a popular trend. Akin to some car dealerships, various clothing stores have a policy of accepting the return of used clothes in exchange for a down payment to purchase new ones. For example, H&M has that allows costumers to donate bags of clothing in exchange for a 15% discount on an item of their choice. The development of hundreds of decentralized and circular business models where the producer is also responsible for the reuse of the product is a likely path to gradually build a global circular economy. These business models, together with the expansion of centralized recycling and upcycling, and the creation of centralized biorefineries, are important components needed to close material loops in the economy.

4. Overview of the most common technologies used for MSW management

In this section, we will discuss some of the most common technologies for managing municipal solid wastes: (incineration, landfilling, open dumps, composting, and anaerobic digestion). The main criteria used to select a given management method for MSWs are properties of the waste, land area available, capital cost, targeted products, as well as energy demand. Sanitary Landfills are mostly used in North America (91%) and Latin America (59%). Incineration is mainly used in Europe (14%). Open dumps are still widely used in regions with developing nations: Asia (51%), Africa (47%), Latin America (31%) [16]. In China, incineration with energy recovery is rapidly growing as the preferred method for municipal solid waste management [13].

4.1 Plastics recycling and disposal

Fig. 14.3 shows the four categories of technologies used in plastic recycling [3]. Primary recycling is used for closing material loops. Mechanical reprocessing (secondary recycling) is limited to single, uncontaminated plastic, resulting in a product with equivalent quality. Tertiary recycling is based on the depolymerization of plastics with the aid of chemical and thermal agents. Chemolysis is used solely for PET and aims to synthesize new polymers with similar properties to virgin plastics. Chemolysis technologies (methanolysis, Glycolysis, Alcoholysis, and Hydrolysis) are, however, all very expensive technologies. The quaternary approach is the incineration of mixed waste streams for energy production.

4.2 Incineration

Incineration, as a method of MSW management, is defined as the destruction of MSW in the presence of an oxidizing agent at temperatures between 850 and 1200°C, generally, in a furnace to generate heat and electricity. The main goal of this technology is reducing the volume and the mass of the waste stream [5,22]. Since incineration requires a relatively small amount of space, regions with space constraints like Europe, Japan, and China, commonly use incineration for MSW management. A drawback of incineration, however, is the high

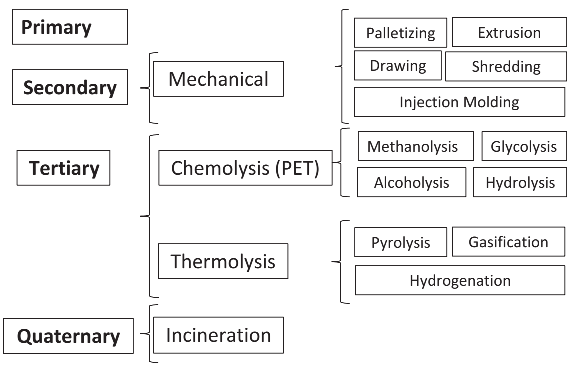


FIGURE 14.3 Different approaches to recycling.

capital and operating costs of incinerators [2,23]. This method achieves approximately 70% of the total waste mass and delivers 90% of the total volume reduction [14,16,24]. During incineration, air pollutants, such as SO_x, CO_x, furans, dioxins, and NO_x, are formed [25]. A better understanding of dioxin formation mechanisms and the introduction of operational and design changes have resulted in a reduction of dioxin concentrations to lower levels, difficult to measure [25,26]. Modern incineration units are composed of the incineration reactor, energy recovery unit, and air pollution control system [5,16]. There are three main wastes from incineration: fly ash, gypsum from cleaning the smoke, and slags (the uncombusted carbon) [24]. Fly ash and air control residues are classified as hazardous wastes that need to be disposed of in underground or in landfills following strict environmental standards [13–15,27]. Glass, magnetic metals, minerals, synthetic ceramics, paramagnetic metals, and unburned organic matter form fly ash [28]. Fly ash from incinerators can also be recovered after detoxification (e.g., washing) for product manufacturing (ceramic products and cement, glass recycling) [24,27]. The slag needs upgrading before it can be used for road construction.

In Japan, MSW incineration fly ash is classified as "general waste requiring special controls." The incineration ash is subjected to at least one of the following treatments: (1) melting and solidification (1400°C volume reduced by half), (2) solidification with cement, or (3) Stabilization using chemical agents [29].

The main advantages of using incineration for processing MSWs are the recovery of energy contained in the waste stream, and the large mass and volume reduction achieved [16]. Incineration also produces little noise, good hygienic conditions, and low odor levels, which facilitate its location within city limits, therefore, reducing transportation costs. The technology, however, cannot be used for waste streams with high water content, low calorific value, and for chlorinated wastes. PVC and other chlorinated wastes result in the formation of HCl and dioxins, which needs special treatment of the off gas from the facility. Incinerators are complex systems that require skilled personnel.

4.3 Landfilling

Landfilling is by far the most used technique for MSW management in developing nations. This technology requires large areas outside city limits. Landfilling of the organic fraction of MSWs (OFMSW) is further problematic. Anaerobic conditions in parts of the landfill result in the emission of between 30 and 70 million tons of methane worldwide to the environment [30] (Hettiaratchi et al., 2015). Compared with CO_2, methane has 20–23 times higher GHG potential [2]. Furthermore, obnoxious odors are also emitted from landfills due to the release of volatile organic compounds containing sulfur developed through putrefaction of parts of food waste [31]. In modern landfills, the biogas is collected by a system of wells and pipes and used in boilers or turbine for electricity and/or heat production [4]. However, only 30%–40% of the total gas generated is typically collected. Spontaneous explosion due to methane gas buildup is possible even with the implementation of this technology. In addition to the release of gases, the presence of heavy metals and xenobiotics in landfills leachate also cause soil and ground water contamination [6]. Landfilling of organic fractions of MSWs has been banned by several countries (for example, Finland, Sweden) [1,2]. In China, all new landfills must be equipped with gas collection and treatment facilities (if the total capacity is greater than 2.5 million tons, and the depth of landfilling is greater than 20 m). These units

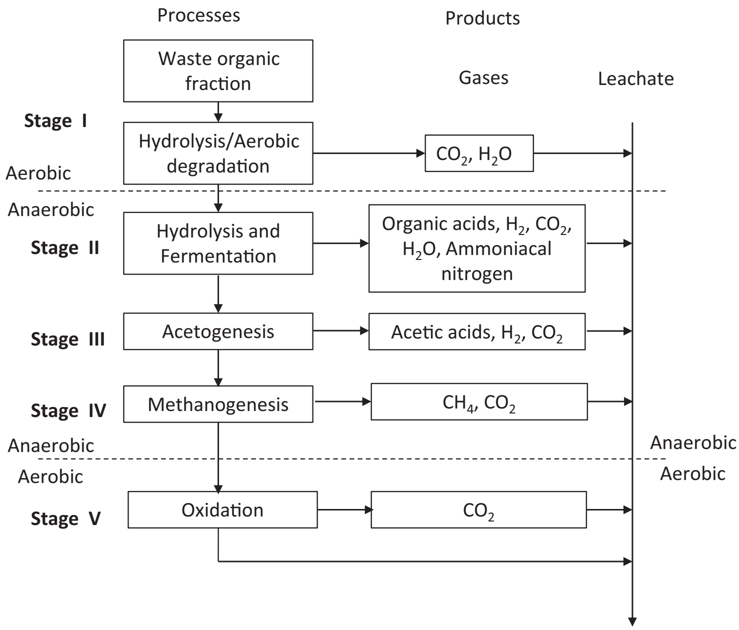


FIGURE 14.4 Main stages and processes of landfills [12].

should be surrounded by a green belt of at least 10 m in width and a buffer zone. The new units must meet stricter leachate discharge standards.

Fig. 14.4shows the five main steps of waste degradation in landfills. The first phase is aerobic. It is responsible for the solubilization of complex organic molecules and the production of CO_2 by hydrolytic enzymes excreted by microorganisms [12]. The resulting soluble products are converted into organic acids, CO_2, and H_2. The methanogenesis step converts the acid into methane with the release of large quantities of greenhouse gases.

From an economic view, landfills might have advantages. They are often the cheapest available option and can be operated without the need for highly skilled personnel. The gas produced can be utilized for power generation. Landfills, however, present many challenges, which is increasingly in focus. The fact that most methane produced in the landfill escapes to the atmosphere and contributes significantly to the overall greenhouse gas emission; the fact that it creates surface runoff during rainfall, which causes soil and groundwater pollution by the leachate; the fact that it contaminates major land areas and makes them uninhabitable for the future. New landfills are difficult to permit today in many areas of the United States and meet major protests from communities in the vicinity each time a new spot needs to be permitted. As a consequence, parts of the waste, for instance, from the City of Los Angeles is transported over long distances into neighboring states, such as Nevada. Finally, the costs to install gas pipelines and leachate treatment units may also be significantly high [16]. As we think in the creation of a circular economy, it is important to remember that our target is to gradually minimize the use of landfills to the point that they will not be needed anymore.

4.4 Composting

The aerobic biological process, called *compositing*, is defined as the process in which organic matter is oxidized to a recalcitrant stable residue with the air of the heat released from the biological process. Feedstocks commonly used at composting facilities are yard debris, mixes of food and yard debris, land-clearing and wood debris, manure and agricultural organics, food waste, and industrial and food processing organic waste. The three main reasons to use compositing are volume reduction, production of a useful stable compost product, and avoidance of methane production. The main composting technologies in the market are windrows, aerobic static pile, in-vessel composting, and Gore composting covers. Windrows method is by far the most common technology in which the pile is mechanically aerated by a pipe network connected to a blower. The use of covers reduces the effect of rain and evaporation by solar energy. Composting has the capacity to process both wet and dry wastes. However, its final product, typically commercialized as a soil amendment, has limited value [6]. Like in the case of landfills, anaerobic digesters, and incineration, composting is not economically viable by selling its soil amendment product. Its economic viability is heavily dependent on tipping fees.

Composting can be done in facilities with wide ranges in size, from a back yard to composting facilities processing more than 100,000 tons of MSW per year. Large facilities accomplish their aerobic process through a variety of process methodologies, including windrow composting, aerated static pile (ASP) composting, and in-vessel composting (e.g., GORE Cover System) [32]. All facilities go through both mesophilic (<45°C) and thermophilic phases (45−80°C), as a result of the aerobic conversion of the waste. The technologies will differ in regard to their pile maintenance, aeration process, and gaseous/moisture control. Regardless of process choice, the composting process produces not just a finished compost product, but also leachate, gases/odors, and contaminants.

The term "leachate" refers to the liquid that is produced when the organic materials are converted to CO_2 and which, as a result of gravity, pass through solids and extracts solutes on its way. In larger facilities, the leachate is recovered by drainage systems and collected in a treatment tank. Treatment methods involve the removal of suspended solids, as well as the reduction of biochemical oxygen demand (BOD). The most common method for meeting these specifications is to store leachate in settling chambers equipped with aeration. The treated effluent can then be discharged from an overflow channel into the main sewer drains or reused on-site. The sediment is usually landfilled, or land applied [33].

A major concern with composting is the odor, as noxious gasses like nitrogen and sulfur are produced along with CO_2. This odor issues increase further when the compost facilities treat putrescent organic materials (i.e., food scraps, lawn clippings), a tendency which is increasing due to focus on diversion and reuse of waste [34]. The most common odorous compounds released in composting facilities are methyl mercaptan, hydrogen sulfide, diethyl sulfide, skatole, ethylamine, ammonia, propionic acid, butyric acid, α-pinene, and butanone [35].

Ultimately, an odor control strategy must address all facility activities that produce emissions. Successful control strategies include compost composition, material holding time, stockpiling protocols, materials handling, and site conditions/facilities. Venting of active and curing compost gases to biofilters is the best available control technology when managing VOC emissions [36]. During active composting, two strategies are utilized for solving the odor problems: (1) well-managed piles that limit anaerobic environments and the need for high airflow rates and (2) capture of composting gasses and treatment in a biofilter [37]. Incorporation of other technologies and facilities across all aspects of the compost yard can be useful for control of odors beyond those being emitted from the active piles [35,38]. In Europe, most large composting facilities are closed indoor facilities to ensure full odor control.

5. Overview of most promising emerging technologies for MSW management

In this section, we will discuss both biochemical (anaerobic digestion) and thermochemical (pyrolysis, gasification, hydrocracking, hydrothermal liquefaction, wet oxidation) emerging conversion technologies. Such technologies are not currently used as extensively as composting, landfilling, and incineration, but they have great potential to be part of MSW biorefineries.

5.1 Pyrolysis

In pyrolysis, the organic material is anaerobically depolymerized in the range of temperatures between 350 and 600°C with the aim of producing a liquid or a solid product. This technology results in a volume reduction of 50−90 wt.% [26]. If the feedstock is a lignocellulosic material, the liquid product is typically called *biooil* and the solid product biochar [16]. Although it is very useful for the processing of all organic fractions in MSW, it is especially promising for the processing of plastics (HDPE, LDPE, PP, PS) with many new plants being built around the world. Pyrolysis is a technology suitable for the processing of materials containing C, H, and O but the presence of S, N, and Cl leads to the formation of pollutants [18]. For example, the processing of the organic fraction of MSW results in the formation of SO_x, NO_x, HCl, and NH_3. To limit the harmful emissions when feedstocks are pyrolyzed, technologies for emission control are needed. At low temperatures, plastic pyrolysis generates pyrolysis oil and wax as its two main products. At high temperatures, the main product is pyrolysis gas [39]. The content of PVC is the most important property defining the pyrolysis processability of an MSW separated stream since PVC leads to the formation of HCl, an intensively hazardous chemical. Pyrolysis units processing feedstocks contaminated with PVC should have a torrefaction step (less than 350°C) for the release of HCl and solvent scrubbers for its removal [18,40].

Although in principle, pyrolysis is a very promising technology for the processing of plastics, the lack of refineries willing and able to process of the resulting oils remains as a major hurdle for commercialization of this technology [17].

The main factors affecting plastic pyrolysis are the chemical composition of the feedstock, particle size, temperature profiles (solid and vapors), solid heating rate, and the residence time of the solid and vapors [18]. The type of reactor used for pyrolysis (fluidized bed, circulating bed, fixed bed, rotary drum) determines the heat transfer mechanism (heat transfer coefficient), the flow patterns controlling mixing, and the residence time of products inside the reactor [18]. Pyropleq, Akzo Nobel, PKA-Kiener, Siemens- KWU, DBA process, Ebara, Hitacho-Zosen, Chiyoda, Cassandra, and Sapporo/Toshiba are among the main companies commercializing this technology.

Most of the pyrolysis reactor technologies consist of three main sections: (1) feeding system, where the raw material is typically heated and melted with the liquid outflow being fed into the reactor (2) a PVC cracking at 350°C is required for feedstocks containing PVC [40], (3) pyrolysis reactor operating at temperatures between 350 and 650°C [18], and (4) a products collector where liquid and solid products are separated and recovered [18].

Plasma pyrolysis, catalytic cracking, and hydrocracking are all technologies that have evolved from conventional pyrolysis [41]. In plasma pyrolysis, plasma is used to generate high enough temperature to decompose the toxic compounds in the gas product. This technology is recommended for the processing of mixed plastics and result in the production of syngas with low tar content and high heating value. Plasma pyrolysis, however, is expensive and consumes large quantities of electricity.

In the case of catalytic cracking (pyrolysis in the presence of a catalyst), a lower temperature is required for higher oil yield. It should be noted that this technology is very sensitive to feedstock contamination and catalyst deactivation. Solid acids are the main catalysts used ($AlCl_3$, HZSM-5, HY, MCM-41) for pyrolysis [42]. The most common function of the catalyst is to crack the pyrolytic into smaller molecules. Zadgaonkar, Smuda, T-technology, Fuji, Amoco, Mazda, Nikko, Reentech, nanofuel, Thermofuel/Cynar are among the most important companies commercializing this technology. Hydrocracking is similar to catalytic cracking, but the process is conducted under an H_2 atmosphere. This technology results in a product of higher quality, although the operation tends to be very expensive due to the high cost of hydrogen. Analogous to pyrolysis, PVC in the feedstock should be avoided.

5.2 Gasification

Gasification is similar to pyrolysis, as it is also a thermochemical conversion technology, although the process is carried out in the presence of oxygen (15%–30% of stoichiometric ratio) at temperatures in the range 600–1400°C. Gasification reactors are typically classified as fixed beds (Updraft, downdraft, crossdraft), bubbling fluidized beds, circulating beds, entrained beds, and rotary kiln gasifiers [43]. The main oxidants used for gasification are air, oxygen, steam, and carbon dioxide. The calorific value of the resulting syngas depends on the oxidant agent used. Air gasification results in a producer gas diluted by the atmospheric nitrogen (syngas calorific value: 4 and 7 MJ/m^3 N vs. methane calorific value: 38 MJ/m^3 N) that is too low to be utilized in gas turbines [43]. Gasification with pure oxygen generates a syngas with a higher calorific value (10–15 MJ/m^3 N). However, the separation of oxygen from the air is very expensive and can only be justified for large-scale units (larger than 100 kt/y). Steam gasification results in a syngas enriched in hydrogen (calorific value 15–20 MJ/m^3 N) but the overall gasification is endothermic [43]. The main product of this process is syngas (a mixture of CO, CO_2 and H_2), which can be subjected to catalytic chemical synthesis to produce different fuels and chemicals (mixed alcohols, NH_3, waxes, diesel, olefins, gasoline, ethanol, methanol, formaldehyde, MTBE, acetic acid, DME) [26,44]. This technology is able to meet existing emission limits and result in a significant volume reduction [43].

The main operational parameters impacting the performance of gasifiers are the equivalence ratio (actual air/fuel ratio divided by the stoichiometric air/fuel ratio), gasification temperature, the residence time of gases and waste, waste composition and physical properties, and composition and inlet temperature of the gasifying medium [43]. The most important parameters that define the performance of gasifiers are cold gas efficiency, hot gas efficiency, carbon conversion efficiency, tar content, and specific syngas flow rate [43]. The term cold gas efficiency is important because, in some applications, syngas needs to be compressed. Hot gases compression consumes too much energy. The hot syn gas produced in gasifiers is typically cooled down before compression. In applications, where syngas is used in a compressed form, only syngas chemical energy is useable.

The main advantage of gasification is that it is a well-established technology with the capacity to break down complex mixtures of plastics, paper, wood, and garden waste, along with food waste, into a simple blend of gases that can be further converted with known mature technologies into value-added products [43]. Furthermore, this technology results in a strong reduction of waste and has limited need for land [43]. However, this technology can only be used on a large scale. The syngas is often contaminated with tar requiring expensive gas cleaning systems. This cleaning is needed before the fuel gas can be used in engines, turbines, and fuel cells.

Because gasification operates at lower temperatures than incineration, the potential alkali volatilization, fouling, slagging, and bed agglomeration is lower than for combustion but still more important than for pyrolysis. During gasification, NOx, and SOx emissions are also formed, but the volume of gas that needs to be treated is much lower than in the case of incineration. Like in the case of pyrolysis, fuel Cl develops HCl, which can be removed with the aid of Zinc and Iron-based sorbents.

Nippon Steel (fixed bed O_2 blown), Ebara-Alstom, Texaco, Lurgi, Hitachi Metals Plasma Arc, Thermoselect Greve-TPS/Ansaldo (CFB on RDF) are among the most common developers of MSW Gasification Systems [3]. Although most of the gasification projects today are designed to produce heat and electricity, some companies like Enerkem (https://enerkem.com/) from Canada are currently integrating gasification into biorefinery concepts. Enerkem is targeting the production of methanol and ethanol [45]. The first Enerkem MSW gasification chemical recycling plant is located in Edmonton, Canada. Enerkem with its partners (AkzoNobel, Van Gansewinkel, Air Liquide, AVR) is planning to build a plant in Rotterdam, the Netherlands, for converting 350,000 tonnes of waste annually into 270 million liters of methanol [3]. Fig. 14.5 shows a typical scheme for methanol production via gasification.

As in the case of pyrolysis, there are several advanced gasification concepts. Plasma gasification is among those with the highest potential for the processing of municipal solid wastes as it has a very high tolerance to feedstocks with low quality. This technology uses plasma torches for the production of syngas with a high level of purity and reduced levels of tar. It also results in the production of an ash product with low content of

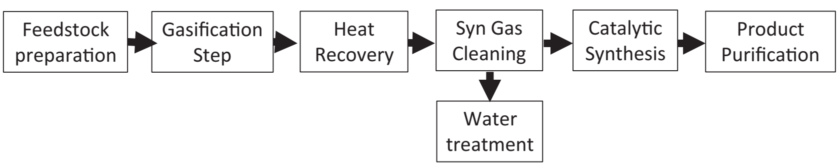


FIGURE 14.5 Outline of a typical gasification plant for methanol production.

contaminants. Hitachi Metals Env. Syst. Co. and Alter NG use plasma torches are located at the bottom of the gasifier to melt inorganics and form glass aggregate and metal nodules [43]. However, its capital and operational costs (mostly due to high electricity consumption 1200−2500 MJ/t waste) [43] are much higher than those of conventional gasifiers. Advanced Plasma Power (APP) in the UK and Plasco Energy Group in Canada are also developing plasma gasifiers [43].

5.3 Hydrocracking

Hydrocracking is conducted at temperatures comparable with pyrolysis (375−500°C); however, it is conducted under pressurized hydrogen (70 atm) in the presence of catalysts to produce stabilized liquid products [3]. This process is mostly used for the processing of molten plastics, excluding PVC [3]. If catalysts are used, the processing temperature is lowered. Hydrogen cost is the main hurdle for the deployment of this technology [3]. Currently, Hiedrierwerke, Freiberg, Bohlen, and ITC are among the most important companies developing this technology [3].

5.4 Hydrothermal liquefaction

Hydrothermal liquefaction (HTL) is the equivalent of pyrolysis for the processing of wet organic streams (sludge, algae, and food waste). In this technology, the thermal degradation occurs in the liquid-phase at temperatures between 300 and 450°C (pressures of 2500−3000 psi). Like in the case of pyrolysis, HTL results in the production of a biocrude oil, gas, solids, and an aqueous phase [46]. The main difference with pyrolysis is that the products of thermochemical degradation reactions are removed by solubilization in water. The oxygenated products derived from cellulose and hemicellulose solubilize in the aqueous phase. HTL processes cannot easily valorize the aqueous phase because the content of organic molecules is relatively low. For overcoming this issue, the aqueous phase can be recycled several times until the content of organics on it makes its utilization viable [47].

5.5 Wet oxidation

Wet Oxidation (WO) and Catalytic Wet Oxidation (CWO) are processes conducted in reactors with conditions similar to those described for HTL (temperatures between 130 and 374°C) in the presence of oxygen or another oxidizing agent (example ozone, hydrogen peroxide). Wet oxidation aims to remove organic pollutants from liquid effluents with the formation of CO_2. This technology was patented by Zimmerman more than 50 years ago. Bubbling column reactors are commonly used for wet oxidation at industrial scales. For WO reactions to happen, the oxygen (or the oxidant agent) has to be converted from gas to liquid. If catalysts are present, the oxidant agent is converted into a free radical that will then attack the pollutant in the solution. Wet oxidation can further be operated to open lignocellulosic biomass materials from waste by using more moderate temperatures and oxygen additions [48]. Through this process, these materials can be converted into ethanol after enzymes addition or methane by anaerobic digestion.

5.6 Anaerobic digestion

Anaerobic digestion is the biological degradation of organic material in the absence of air. Biogas is the primary output obtained. The quality and the composition of the output gas depends on the composition of the feed materials, as well as the operating conditions of the reactor [4]. Typically, the biogas consists of CH_4 (50−75 vol. %), CO_2 (25−50 vol. %), and a small amount (1−15 vol. %) of other gases, such as NH_3, H_2S, and water vapor [49]. Anaerobic digestion of the organic fraction of MSW (OFMSW) produces not only methane gas but also a digestate, which can function as a biofertilizer [50]. There are four steps characterized by different microbial groups active during anaerobic digestion of organic fraction of MSW. In the first step, the complex organic compounds like proteins, fats, and carbohydrates are converted into smaller molecules like amino acids, fatty acids, and sugars. During the second step of anaerobic digestion, the monomers produced in the first step are converted into volatile fatty acids like butyric acid, propionic acid, and valeric acid. This process is called *acidogenesis*. In the third step of anaerobic digestion, the VFA's produced during the second step of anaerobic digestion are converted to acetate, H_2, and CO_2 and the process is called *acetogenesis*. In the fourth step of anaerobic digestion, the acetate, CO_2, and H_2 are converted to methane by methanogenic bacteria. This process is called *methanogenesis* [51]. Anaerobic digestion of MSW is a cost-effective and environmentally friendly technology as compared to the thermal technologies and can be used for the treatment of OFMSW.

AD is classified based on the operating parameters and reactor design in (1) batch versus continuous, (2) psychrophilic, mesophilic, and thermophilic, (3) plug-flow, complete mix, and covered lagoons and (4) wet versus dry [52]. The high potential energy and nutrients in the OFMSW, especially in food waste and yard waste, can be used for the production of green energy lowering the carbon footprint of waste management [53,54]. Anaerobic digestion has been used for the production of biogases from different types of substrates, such as manure, sewage sludge, waste water, food waste, and lignocellulosic materials. It is known that anaerobic degradation of OFMSW takes, place naturally in landfills [4]. It is also being used for the OFMSW, but depending on the source-sorting principles, the waste can be more or less digestible. If green and woody waste is part of the collection, it can be difficult to get a decent efficiency of AD to convert carbon into biogas and pretreatment will be necessary to improve the overall conversion rate. Currently, different pretreatment technologies are being used to overcome barriers for waste streams with a high degree of lignocellulosic materials. Furthermore, codigestion is often used to improve the C/N ratio, for instance, by mixing sewage sludge with the organic fraction of municipal solid wastes [55]. Nielfa et al. [56] studied the codigestion of OFMSW and Biological Sludge and found that the optimum codigestion was at 80% OFMSM and 20% Biological sludge. Jain et al. [52] published a review on the operating parameters and the effect of mechanical, thermal, chemical, and biological pretreatment on AD. Table 14.3 shows the main factors affecting the anaerobic digestion of OFMSW.

The anaerobic digestion is not widely used in the world for the treatment of OFMSW because more time and space is required for the AD process as compared to other waste management technologies [57]. The low yield of biogas from the anaerobic digestion of OFMSW with a high content of lignocellulosic materials is the main challenge of anaerobic digestion of this raw material. The lower yield of methane is due to the complexity of the

TABLE 14.3 Main parameters affecting the anaerobic digestion of OFMSW.

Parameter	Range	Observations	Ref.
Temperature of the reactor	T < 30°C (psychrophilic) 30 < T < 40°C (mesophilic) 50 < T < 60°C (thermophilic)	Reactors typically insulated Optimum conditions 35–55°C Below 10°C activity of methanogens stops Methanogens produce a satisfactory amount of gas between 25–30°C	[84]
Composition of the feedstock	OFMSW consists of a biodegradable fraction and an inert fraction. Activity of methanogenic bacteria is dependent on the concentration of solids in the feed material (bacterial activity is good at a solid concentration of 6%–9%).	Optimum charge with the season (summer: 6% solid content, winter: 10%, spring: 20%). When the temperature of the reactor is very low, then the material degradation rate during anaerobic digestion is also low, and it is recommended to feed the reactor with a substrate that has a higher solid concentration	[85]
pH	Optimum pH for methanogenic bacteria: 6.5–7.8	pH indicates the proper working of the reactor. VFA accumulation can cause the pH to drop. Methanogenic bacteria cannot grow at lower pH. Conditions called: Souring of the reactor.	[52,86]
Carbon to nitrogen ratio	C/N ratio: 20–30 (Anaerobes can grow properly) Optimal C/N ratio for the anaerobic bacteria: 25 Higher C/N ratio (more than 30): Rapid consumption of N and deficiency to grow	Lower C/N ratio can be due to the presence of high concentrations of food waste. It can cause accumulation of ammonia. Accumulation of ammonia can increase pH more than 8.5 and affect the quality of digestate used as a biofertilizer	[87]
Loading rate (amount of substrate per unit of volume per day)		Gas production highly dependent on the loading rate. Gas production is high at lower loading rates. Inhibition occurs inside the reactor because the methane-producing bacteria grow slowly as compared to the acid-forming bacteria.	[88]
Nutrients for the bacteria		Besides carbon, hydrogen, and oxygen, the bacteria also require other elements like sulfur, potassium, sodium, nitrogen, and magnesium.	[88]
Hydraulic retention time (HRT) (time the organic material remains inside the reactor)	Colder regions: Up to 100 days Warmer regions: 30–50 days. Dry anaerobic digestion: 14–30 days Wet anaerobic digestion process: 3 days	HRT dependent on the climatic conditions. Low retention time: bacteria can be washout of the reactor. Long retention time: the volume of the reactor will have to be increased.	[89,90]
Mixing		Sufficient mixing is required inside the reactor for proper contact between bacteria and the substrate and for the distribution of nutrients evenly in the reactor.	

material due to which the hydrolysis of the OFMSW during AD is very slow [58]. Moreover, the OFMSW contains a high percentage of solids, and there is no reactor developed, which can handle high solid materials for anaerobic digestion and produce a high yield of methane [59]. Ammonia toxicity, which mainly affects methanogens, is another challenge in the anaerobic digestion of OFMSW, especially when using high concentrations of food waste [15].

The presence of contaminants like glass, packaging material, rags, metals, decrease the efficiency of the anaerobic digestion of OFMSW. These materials can also cause operation and maintenance problems [60]. As discussed, lignocellulosic materials are difficult to degrade during the anaerobic digestion process due to the strong bonding between cellulose hemicellulose and lignin. Besides this, the presence of heavy metals in the OFMSW part is another issue because these heavy metals are inhibitory for anaerobic bacteria if their concentration is too high [61]. Phthalate contamination can occur due to the higher concentrations of plastic in the waste, which deteriorate the quality of the digestate and prohibit the use of the material as a fertilizer on fields [62]. The presence of rags and plastic bags can cause wear and tear of pumps and valves, as well as choking of different pipelines in the digester system, which will increase the cost of maintenance and can decrease the gas production as well [62].

OFMSW is not favorable for anaerobic digestion because of higher concentrations of inert materials; but SS-OFMSW and SC-OFMSW are generally good substrates, which result in three times more biogas as compared to the SS-OFMSW [63]. C/N ratio is also an important factor in the anaerobic digestion of OFMSW so it is recommended that the OFMSW should be mixed with a substrate having lower C/N ratio to balance the input [64]. For this purpose, the sewage sludge and animal manure are commonly used. The anaerobic digestion of OFMSW (with high concentrations of lipids and proteins) can further be problematic because these products rapidly degrade during aerobic digestion and cause VFA accumulation, pH drop, and ammonia inhibition. Overall, it is recommended that careful analysis of the OFMSW should be done before its use as a substrate for AD process, and if the OFMSW contains materials which potentially could result in process inhibition, it is better to implement codigestion with suitable materials [63].

The feasibility and the potential of anaerobic digestion of the abundantly available OFMSW can be enhanced by the production of other value-added products from the process than biogas, such as hydrogen, ethanol, and lactic acids [65]. Moreover, the process can further be tailored for the production of bioplastic precursors, enzymes (amylase and lipase), chemicals (acetone and butanol), and biopesticides. Finally, OFMSW can also be used to produce Volatile Fatty acids, which can be an important platform of molecules for biofuels and bioproduct production. It has been estimated that the VFA production will result in 31% savings from the anaerobic digestion process [66].

Other biotechnological processes for the utilization of MSWs have been studied [2]. Of particular interest is the production of ethanol with yields as high as 430 g/kg of dry material produced, as reported in the literature [2,67–70]. The production of H_2 by fermentation (photofermentation or dark fermentation) or photosynthetic means (direct biophotolysis of water by algae and cyanobacteria or bioelectrohydrogenesis in microbial fuel cells) has also received great attention [2]. Dark fermentation is, by far, the cheapest process for H_2 production [2]. Hydrogen yield as high as 185 mL H_2/g volatile solids (from lard fermentation under stirring and CO_2 scavenging) has been reported [2,71–73].

6. Main challenges

The main challenge for processing MSW with emerging technologies is our capacity to separate wet and dry fractions so that they can be processed by adequate technologies. Another major challenge is how to integrate these technologies into new biorefinery concepts so that all the fractions from MSW can be converted into useful products. Perhaps, the best example of this trend is Enerkem's biorefinery concept aiming to produce methanol and ethanol via gasification of MSW. In this section, we will discuss the challenges in developing new biorefinery concepts using emerging technologies for the processing of municipal solid wastes.

Biorefinery refers to an integrated system of technologies maximizing the use of waste streams for the production of multiple, valued coproducts [74,75]. In principle, it is possible to develop many different biorefinery concepts for the processing of MSWs; however, the selection of the most promising concept has to be based on a thorough analysis of the economic, environmental, and social performance indicators of these concepts [74,75]. Garcia-Nunez et al. [75] proposed a methodology for evaluation of biorefinery alternatives (See Fig. 14.6). The author used this methodology for the analysis of palm oil biorefinery concepts [75].

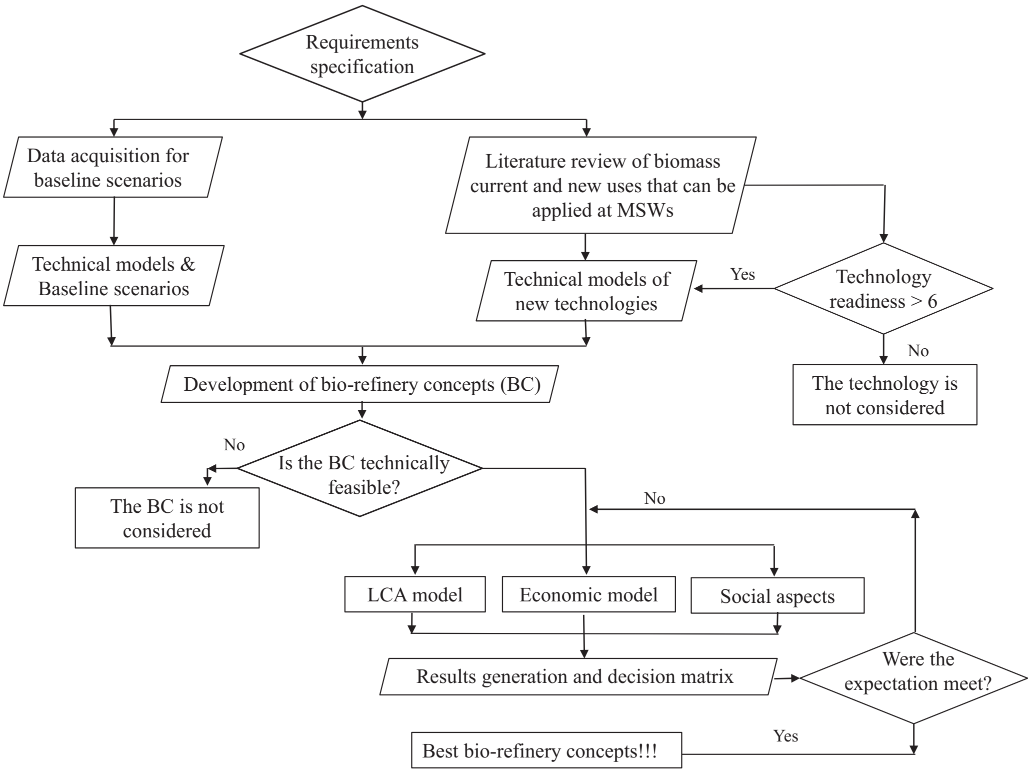


FIGURE 14.6 Generalized strategy for the design of novel biorefinery concepts [75].

While developing new biorefinery concepts for the processing of MSWs, it is critical to examine the different technologies described in the first section of this chapter (composting, anaerobic digestion, gasification, pyrolysis). The first step is to collect data on an existing unit (composting, anaerobic digestion) to build what we will call the base line scenario [75]. The baseline scenario is basically the mass and energy balance and the technoeconomic analysis of an existing unit for processing MSWs (a composting unit, anaerobic digestion). Based on a thorough literature view, the analyst should choose technologies that have been tested for the processing of streams (inlet or waste) associate with the base technology targeted. Although there are several technologies that have been studied for the processing of MSW streams only a few of them are at a sufficiently high level of readiness to be used. Technology readiness level is an indicator created to describe the level of maturity of a given technology. Once those technologies have been identified, the analyst should then propose schemes to integrate the baseline technology with emerging technologies. Fig. 14.7 shows a cartoon created by the Washington State University to visualize how different technologies come together to process municipal solid wastes. This vision includes baseline composting and recycling of contaminants (metals, glass, plastics, and useable paper), and also emphasizes the use of additional technologies to more effectively treat particular organic streams reaching the facility (i.e., anaerobic digestion of wet/putrescent material, torrefaction/pyrolysis of dry wood material). By treating different fractions of the waste with ideal conversion technologies, important gains in air/odor, water, and climate effect can be accomplished. Additional processing units are added in order to maximize coproducts (i.e., nutrient recovery, greenhouses, biogas/CNG purification) while also providing additional environmental gains.

Many technically viable integrated biorefinery concepts can be developed, but because of the limited amount of financial resources and feedstocks it is crucial to choose the concept, which offers the best economic, environmental, and social performance and with known performance indicators.

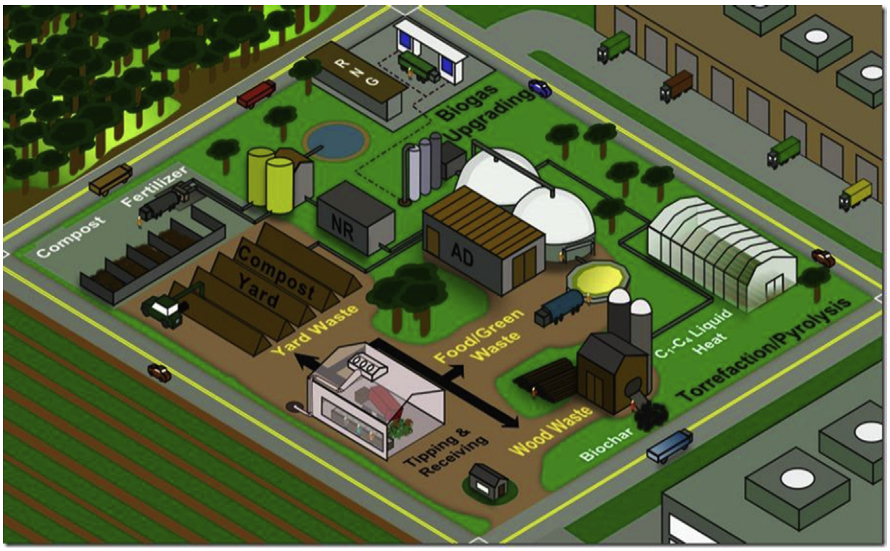


FIGURE 14.7 WSU biorefinery vision.

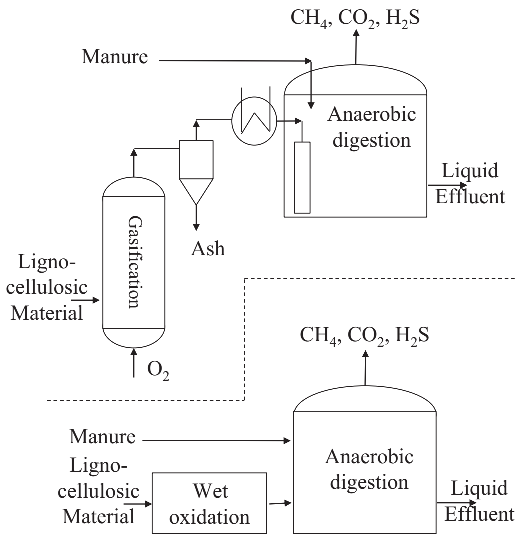


FIGURE 14.8 Example of integrated concepts (biorefineries) for the production of biogas from lingocellulosic materials.

For example, one of the main challenges of anaerobic digestion is that this technology cannot process lingo-cellulosic materials. Fig. 14.8 shows two potential combinations between anaerobic digestion wet oxidation [48,76,77], and gasification [78]. In both cases, the lignocellulosic material is processed by a thermochemical technology for the production of a stream that can be processed by AD (use of thermochemical technology for pretreatment) [79]. Similar concepts could be developed for pyrolysis [80] and hydrothermal liquefaction [81,82]. In this concept, thermochemical technologies (gasification, wet oxidation) are used to depolymerize the recalcitrant structure of lignocellulosic materials. The resulting streams (aqueous phase rich in sugars and acetic acid or syngas) are then anaerobically digested to produce methane.

More complex biorefinery concepts could be developed if the emerging technologies are carefully evaluated to identify potential synergistic effects. For example, the biogas produced from anaerobic digestion systems needs to be cleaned (removal of H_2S and CO_2) before it can be injected into the pipelines or used as fuel in cars. The effluents of anaerobic digestion systems contain nutrients (N and P) that need to be removed to avoid eutrophication if the material is not used as a fertilizer. The development of carbonaceous adsorbents from the pyrolysis of anaerobically digested fibers with the capacity to remove P from AD liquid effluents [21] and H_2S from the biogas [83] is opening the door to advanced biorefinery concepts with much better environmental performance than current systems.

Although the gradual integration of emerging technologies in novel biorefinery concepts to accomplish a thorough utilization of all MSW fractions is still in its infancy, there are some promising concepts worth mentioning. Enerkem (https://enerkem.com/) and Anaergia (https://www.anaergia.com/) both convert waste into useful resources. In the last 25 years, Anaergia has built more than 1600 plants focusing on MSW, wastewater, and agri-food resource utilization. This company has developed its own technologies (high solid digesters, mechanical biological treatment systems, membranes for water reuse, technologies for nutrients, and digestate management, pyrolysis of biosolids, OREX) which allow them to develop unique biorefinery solutions for the processing of solid and liquid wastes. The core technology for Anaergia is anaerobic digestion. Enerkem focuses on the conversion of MSW into fuels and chemicals (ethanol and methanol) through gasification. These organic molecules are intermediary building blocks for olefins and acrylates. In its innovation process Enerkem is developing new chemical processes to bolt-on to its current waste to chemicals equipment and further grow its gasification-based biorefinery concept.

7. Conclusions and perspectives

Incineration, landfilling, and composting are the most common technologies used today for handling municipal solid wastes. Although very robust, these technologies result in low value added products. Together with centralized recycling, the development of circular companies and centralized biorefineries are critical pieces to close the C loop. Anaerobic digestion, pyrolysis, hydrothermal liquefaction, gasification, and wet oxidation are environmentally friendly and cost-effective emerging technologies with the capacity to handle most of the fractions of municipal solid waste. These technologies can also be integrated into biorefineries to get the maximum use of each of the fractions in municipal solid wastes. Some examples of potential MSW biorefineries were presented. In the years to come, we expect to see new developments in MSW separation technologies and the testing of novel MSW biorefinery concepts. The development of new policies, business models for circular companies, and technologies for these new business models, are major steps toward creating a circular economy.

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Further reading

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