Chapter 7
Waste to Energy in Circular Economy

Anh Tuan Hoang, Hoang Phuong Nguyen, Ashok Pandey, Eric Lichtfouse, Ibham Veza, Shams Forruque Ahmed, Ümit Ağbulut, Xuan Quang Duong, and Xuan Phuong Nguyen

Abstract Humans are producing ever-increasing volumes of waste and contaminants, and it is not difficult to understand that resource exploitation is increasing in tandem with resource depletion. When compared to the previous century, today's global resource utilization, economic activity, and population are all considerably larger. Devastating environmental degradation, contamination, and climate change are the results of unprecedented levels of resource utilization to satisfy human needs.

A. T. Hoang (✉)
Faculty of Automotive Engineering, Dong A University, Danang, Vietnam
e-mail: hatuan@hutech.edu.vn

H. P. Nguyen
Academy of Politics Region II, Ho Chi Minh City, Vietnam

A. Pandey
Centre for Innovation and Translational Research, CSIR-Indian Institute of Toxicology Research, Lucknow 226001, India

Centre for Energy and Environmental Sustainability, Lucknow 226029, Uttar Pradesh, India

Sustainability Cluster, School of Engineering, University of Petroleum and Energy Studies, Dehradun 248007, India

E. Lichtfouse
State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, PR China

I. Veza
Centre for Automotive Research & Electric Mobility (CAREM), Institute of Transport Infrastructure (ITI), Universiti Teknologi PETRONAS (UTP), 32610 Seri Iskandar, Perak, Malaysia

S. F. Ahmed (✉)
Science and Math Program, Asian University for Women, Chattogram 4000, Bangladesh
e-mail: shams.ahmed@auw.edu.bd

Ü. Ağbulut
Department of Mechanical Engineering, Faculty of Engineering, Düzce University, Düzce 81620, Türkiye

X. Q. Duong
Institute of Mechanical Engineering, Vietnam Maritime University, Haiphong 04210, Vietnam

S. A. Bandh et al. (eds.), *Renewable Energy in Circular Economy*, Circular Economy and Sustainability, https://doi.org/10.1007/978-3-031-42220-1_7

Recent global energy consumption levels, as well as an over-reliance on waste disposal and emissions rather than reusing and recycling, are clearly unsustainable. Thus, it is challenging to maintain the conditions for long-term socio-economic and environmental stability, indicating that fundamental changes in the organization of energy resources and waste flows, namely the resource economy, are critical. In addition, the waste-to-energy approach has been offered as a viable solution for decarbonizing the transportation and energy sectors; its primary goal is to recover waste energy in the circular economy. The purpose of this chapter is to examine the role and principles of the circular economy in the design of waste treatment facilities.

Keywords Waste-to-energy · Circular economy · Barriers · Policy and technologies

7.1 Introduction

The worldwide population has been expanding at an alarming rate, with the world population estimated to reach 9.7 billion in the year 2050 and 11 billion by the end of the century (Sharma et al. 2020b). Industrialization, urbanization, and overpopulation are viewed as the underlying causes of the issues mentioned above. Huge growth in energy use and the generation of solid waste are the two main concerns facing the globe. Fossil fuels (such as coal, natural gas, and petroleum) are extensively utilized in order to fulfill the continuous energy demands (Mishra et al. 2019; Mehta et al. 2019). However, the non-renewable nature of fossil fuels is alarming since they produce significant problems such as increased fuel consumption, economic concerns, and climate change. Overuse of fossil fuels has led to the discharge of harmful gases such as NOx, CO_2, SO_x, CH_4 and others, which have noticeably contributed to climate change, global warming, biodiversity loss, and acid rain, all of which have serious consequences for living things and endanger the environment (Malla et al. 2022; Sharma et al. 2020a). Moreover, a shortage of energy supplies could result in considerable increases in fuel prices, causing budgetary issues. Besides, energy consumption was determined by population, which was expected to increase by 50% by the year 2035 (UNDESA 2018). Apart from hazardous emissions discharged from transportation, the growing population also led to an increase in waste generation. It was anticipated that waste created each day in the world has increased to 3.5 million tons/year and by 2025, it could reach 6.1 million tons/year, as shown in Fig. 7.1 (Makarichi et al. 2018).

Present Address:
X. P. Nguyen
PATET Ressearch Group, Ho Chi Minh City University of Transport, Ho Chi Minh City 72300, Vietnam

A. Pandey
Kyung Hee University, 26 Kyungheedae-ro, Dongdaemun-gu, Seoul 02447, South Korea

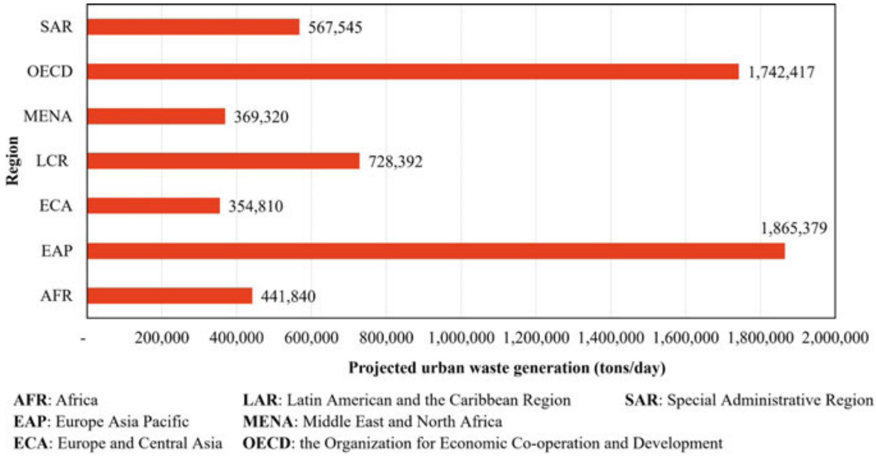

Fig. 7.1 Estimated waste generation by region in the world by 2050 (Makarichi et al. 2018)

It is clearly stated that uncontrolled carbon dioxide (CO_2) emissions released into the atmosphere are considered to be a threat to the natural habitat; therefore finding alternate energy solutions is critical for the world's future stability. In addition, the waste poses a threat to both environmental quality and human health, hindering the development of the economy and society. If municipal solid waste is not effectively handled, it would consume vast amounts of land as well as impede national development. Hence, it is critical to foster the building of a waste-to-energy (WtE) system in a circular economy for sustainable development.

WtE plays an essential part in facing rising waste generation. WtE is considered an appealing way for recovering energy and usable materials as a result of depleting fossil fuel supplies and the production of sustainable energy (Dong et al. 2019). Since last century, generating and employing energy from solid waste combustion is a notion that has been applied in Europe. However, concerns over the quality of groundwater and a lack of space for landfilling prompted Japan and several European nations to begin huge building projects for WtE strategies in the 1960s. Predictions for the number of new, cutting-edge WtE facilities developed by 2020 ranged from 60 to 80, depending on how many are needed to meet EU WtE requirements. The reported percentage of EU energy consumption met by WtE is 1.5% (Mayer et al. 2019). Scandinavian countries have supported the WtE for a long time, and some Asian nations including China, Japan, Singapore and Taiwan have the most WtE facilities in the world. Japan, for instance, has solved its solid waste problem by handling approximately 70% of waste in WtE plants. In addition, China is among the biggest markets for the construction of WtE plants. Indeed, by 2020, the capacity of Chinese WtE was 193 million tons, with about 510 WtE factories, in comparison with the EU WtE capacity which was 96 million tons, and the US WtE capacity is approximately 27 million tons (Themelis and Ma 2021). In this context, the future aim of modern WtE has shifted from "waste treatment field" to "energy and resource generator" (Arena 2015). The construction of WtE as district energy system for the society supported the "win–win" mentality circular economy concept, indicating a prosperous economy and a clean environment could coexist (Balaman et al. 2018). WtE offered a circular relationship between economic growth and greening in order to address existing environmental issues as well as resource limitations by enhancing the efficiency of resource usage in terms of energy generation and the utilization of renewable kinds of energy. In this chapter, WtE would be assessed from the perspective of the circular economy. The techno-economic feasibility of waste-to-energy facilities will also be examined.

7.2 Role of Waste-to-Energy in the Circular Economy

Material flows and their roles (as shown in Fig. 7.2) that waste recycling and WtE can play in a circular economy. The circle illustrates activities in various areas, such as agriculture, services, industry, residences, and waste generation. Recycling is thought to be the most sustainable option for waste treatment for the vast majority of waste. The most appropriate treatment strategy for the many kinds of waste created in a sustainable circular economy is evaluated by economic, social, environmental, and health factors (Van Caneghem et al. 2019).

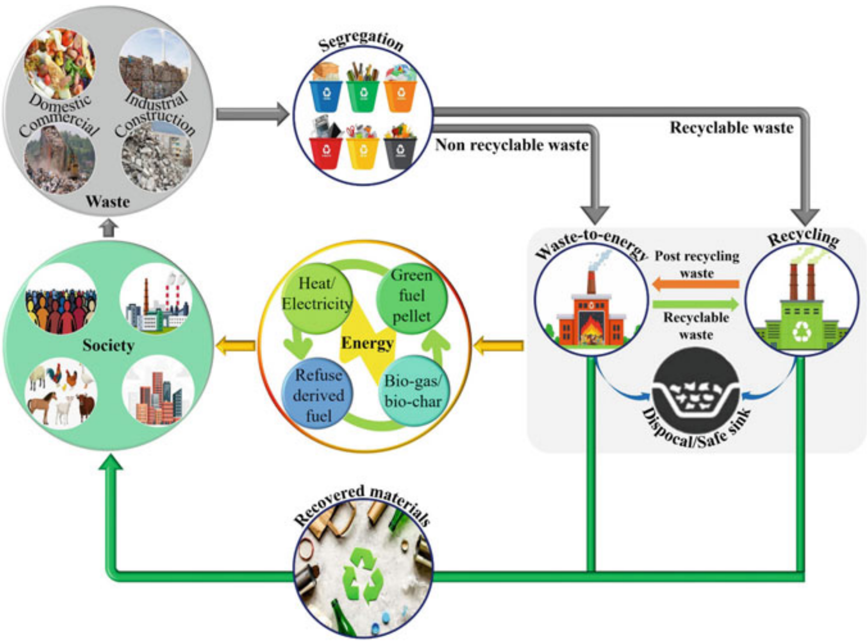

Fig. 7.2 WtE scheme and role of waste in the circular economy

The conventional economic chain is characterized by a one-way flow of "crude materials and energy collected from the environment as well as manufacturing activities and home consumption and contaminants." Besides, traditional economies are known for high emissions, high energy use, and limited resource employment. On the contrary, the energy and material's circular flow provided by a CE is characterized by minimal emissions, low consumption of energy, and high resource use level (Xiao et al. 2020). In the traditional economy, humans utilized natural resources from the ecosystem in order to fulfill the demands of their products as well as living activities. As a result, waste and contaminants are continuously released into the soil, water, air, and the environment during the manufacturing process. Reusable waste, on the other hand, can be recycled or converted into energy in a circular economy, including charcoal, green fuel pellets, biogas, electricity, heat, and refuse-originated fuel. The circular economy is fundamentally a financial framework that substitutes the traditional linear economy by reducing, recovering, recycling and reusing resources in order to achieve sustainable development as well as obtain economic prosperity, environmental quality, and social equality (Kirchherr et al. 2017). Constructing a WtE supply chain is structurally crucial for achieving circular economy goals by ensuring sustainability in the plan and operation of transportation systems and energy via material recovery to produce bioenergy (Boloy et al. 2021). Energy is transformed from waste via WtE and it would be returned to society which includes the recycling industry. In the last few decades, a steam boiler was often used in a WtE plant to recover energy from hot combustion gases aiming to produce power generation, resulting in a maximum total energy efficacy of up to 80% (De Greef et al. 2018). Besides, some solid materials recovered after the WtE process could be used for subsequent recycling. For example, bottom ash, known as the most significant WtE's residue, was a heterogeneous substance composed primarily of metals, ash, and stones. The bottom ash treatment during the WtE process was greatly enhanced over the previous decade aiming to boost the rate of recovery and promote the separated materials' purity, allowing the recycling of nearly the whole bottom ash portion (Kahle et al. 2015). Bottom ash from the WtE process could be used as an uncontained building material, as a substitute for cement, sand, or gravel in construction activities, as a feedstock in the generation of ceramic material, and as raw materials in manufacturing cement (Verbinnen et al. 2017). Aside from heavy metals, chlorides may restrict the utilization of bottom ash in concrete and cement applications (Van Caneghem et al. 2016). In this approach, WtE served as a gatekeeper for the circular economy, allowing materials to be recovered from non-recyclable waste while ensuring that recovered materials were free of harmful chemicals (Van Caneghem et al. 2019).

WtE is universally recognized as an effective strategy for limiting the production of greenhouse gas emissions and mitigating climate change. In addition, WtE is identified as a critical technique to alleviate greenhouse gas emissions. WtE is also important for biodegradable waste since removing it from landfill decrease methane emissions, as reported by Jeswani and Azapagic (2016). It was demonstrated that one ton of biodegradable waste being shifted from a landfill to anaerobic digestion for the production of fertilizer and biogas could prevent up to two tons of CO_2

equivalent emissions (Bernstad et al. 2012). Regarding the organic part of the separately collected waste, like garden garbage and kitchen waste, anaerobic digestion with fertilizer recycling may be a viable management alternative (Malinauskaite et al. 2017). Owing to its potential for greenhouse gas reduction, WtE facilities in the EU are unnecessary to have credits or a permit for CO_2 emissions. In the EU, waste-derived energy carriers were used in urban energy systems such as electricity, transportation and natural gas. They replaced the primary energy carriers, which led to a decrease in the consumption of fossil fuels and non-renewable energy. Owing to the connection between waste and energy, waste planning required coordination with the urban planning and energy system. Generated energy carriers could be utilized to power waste management systems on a local or larger scale, advancing the Circular Economy's "closing the loop" notion. As a result, it was necessary to integrate the development of an energy system (Persson and Münster 2016), management of resources, as well as an energy system and urban waste coupling (Tomić et al. 2017; Tomić and Schneider 2018). Even though this technique ensures high recycling rates for waste, it must also take into account the quality issue of recyclables, the consequences on human health and the environmental issues associated with recycling at the destination. Therefore, the critical and core goal for the recycling sector is not to increase recycling rates, but rather to produce recyclables of higher quality (ISWA 2018).

7.3 Waste-to-Energy Technologies

7.3.1 Thermal Technologies

Thermal WtE conversion methods typically include all thermal processing approaches to produce heat, gas, and oil from waste. Figure 7.3 shows the standard parameters as well as synthesized products of several thermal WtE methods (Tsui and Wong 2019).

As reported by Suthar et al. (2016), the most extensively used technology is waste-to-energy incineration, which is essentially the burning of waste materials operated under high temperatures, with electricity and heat as its principal outputs. Previously, incineration was thought to be primarily employed aiming to minimize the volume of waste (land conservation) and to eliminate toxic materials. Because of the lengthy history, incineration was commonly paired with heat and energy recovery units, so significantly enhancing their application values and performance. In comparison with other thermal WtE methods, waste-to-energy incineration was conducted under the conditions of substantially lower temperatures and in an environment with reduced oxygen, which was related to distinct product yields and reactions. Systems of WtE incineration offered various benefits, including recovery of energy, the reduction of GHG emissions, and savings of resources (Cui et al. 2020). An incineration factory with a working life of 30 years required less than 100,000 m^2 of land to treat one

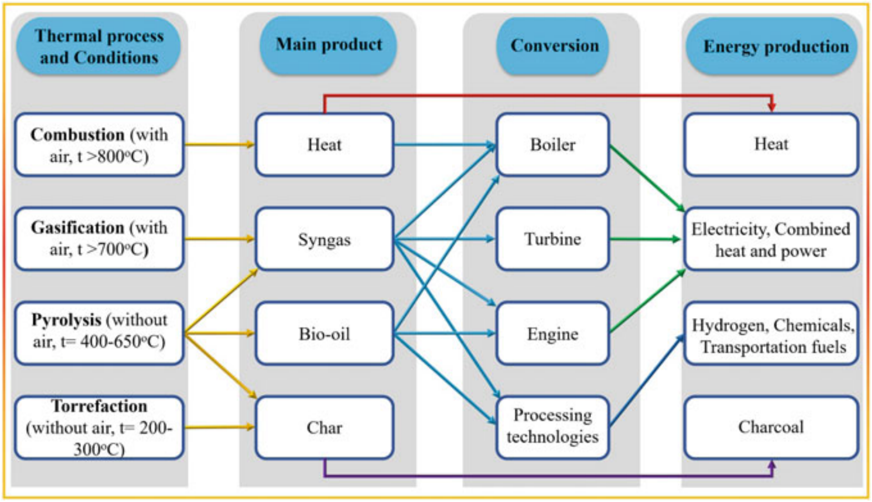

Fig. 7.3 Thermal methods for WtE processes (Makarichi et al. 2018; Sanlisoy and Carpinlioglu 2017; Chen et al. 2018; Tsui and Wong 2019)

million tons of waste each year, but landfilling required 300,000 m^2. Sweden and Denmark were the pioneers in applying incineration, with incineration generating about 5% of Denmark's energy consumption and 14% of total domestic heat usage in their national systems of energy in 2005 (Bosmans et al. 2013). When one ton of garbage is utilized to produce energy, about 1.3 tons of carbon dioxide might be removed from the atmosphere if the same amount of energy were produced by fossil fuel-powered power plants. According to the combustion methods and composition of waste, the final mass conversion proportions of waste to fly ash and ultimate bottom ash were approximately 10:1 and 10:2.5, respectively, with 75% of the total waste mass being released as of gas (Malindzakova et al. 2015). Moreover, waste incineration has a somewhat narrower range of carbon emission factors (corresponding to 0.04–0.14 kg-CO_2/MJ) for producing electricity compared to fossil-fuel power plants (Astrup et al. 2015). By 2015, there were 1179 waste incineration plants operating globally, with a total capacity of approximately 700,000 t/d (Lu et al. 2017). China, the European Union, Japan, and the United States ranked first through fourth, with anticipated capacity of 255,850 t/d for China, 207,104 t/d for the EU, 92,203 t/d for Japan, and 88,765 t/d for the United States (Cui et al. 2020; Lu et al. 2017; Michaels 2014). Notably, the robustness of incineration in the handling of diverse waste was its distinctive characteristic. Given its maturity, incineration was likely the most effective solution to the problem of rapidly expanding populations producing waste at the present time. Although the convenience of WtE incineration was normally preferred, it led to severe consequences including depleting the natural ecosystem of material reserves as well as pure air. WtE incinerators were also designed to dispose of waste safely and effectively in addition to generating usable energy. Therefore, they were regarded as the most advantageous solution for sanitary landfills, particularly in big and medium-sized communities where landfill space might be restricted.

In addition to WtE incineration, gasification is a process that is intermediate between combustion and pyrolysis process in which it is related to material's partial oxidation. In other words, oxygen is introduced, yet not in sufficient quantity for complete combustion to occur. Temperatures typically range between 650 and 800 °C. Even though it was predominantly exothermic, it was noted that this process could be required to initiate and sustain the gasification process (Seo et al. 2018). In comparison to waste incineration, waste gasification was observed to be favored over incineration since it produced a syngas product which could be utilized in a variety of ways. Furthermore, gasification produced uniformly high-quality syngas from diverse and complicated residual waste. Only gasification could offer multimodal products like heat, liquid fuels, power, chemicals, cooling, and gaseous fuels (Rauch et al. 2018). Gasification also allowed for efficient power generation with excellent integration with existing power generation equipment including gas engines, steam cycles, and gas turbines. Apart from that, the gasification of wastes was a prelude to biomass gasification on a large scale and would enable carbon capture and storage, which would otherwise result in detrimental greenhouse gas emissions (Saghir et al. 2018). It was noticeable that gasification was known as incomplete oxidation in which the amount of oxygen was less than required for full stoichiometric combustion. Actually, partial oxidation was accomplished with the use of gasifier agents like CO_2, in comparison with WtE incineration. The generation of SO_2, dioxins, and NOx was thus better regulated, and the overall flue gas volume was reduced, resulting in less costly gas treatment devices. Because of the minimum volume of flue gas, pollutants became more concentrated, allowing for more effective physicochemical treatment in which tiny particle matter was collected. Actually, the employment of air as an oxidant was considered a less expensive choice in terms of capital investment; however, it might not provide syngas with high calorific value, so a compromise had to be struck throughout the selection process (Gañan et al. 2005). Since the range of syngas heating values was from 4 to 40 MJ/kg (McKendry 2002), they had a significant impact when choosing a gasifier. Certain waste types, such as plastic waste, biomass-originated material, and paper waste and packaging were already gasified (Win et al. 2019). Nevertheless, pre-treatment was often required regarding mixed waste, and the mechanical biological treatment's additional energy consumption should be considered in the total energy balance (Deng et al. 2017). Three main system devices used in this process were: fuel bed (including rotating, fixed, and moving), entrained flow, and fluidized bed (Qi et al. 2019). Some factors such as the process magnitude, as well as the requirements of upstream and downstream processing all, had an effect on the choice of gasifier system. In addition, capital costs, the application and quality of syngas products all impacted the choice of oxidant kinds like air, O_2, CO_2, or steam. In order to recover extra energy, the majority of commercial gasification units that handled waste-originated feedstock used a secondary combustion chamber for syngas burning as well as energy recovery from a steam circuit. Moreover, at different phases of the gasification process, plasma gasification techniques with high temperature could also be in use. This plasma technology could produce tar-free clean syngas (Seo et al. 2018). In addition, there existed many thermal treatment factories relying on relatively modern processes like the Ebara fluidization process, direct smelting, and melting procedures including Thermoselect gasification (Suzuki 2007). The above-mentioned processes generated glass fibers which were not only less toxic compared to traditional WtE combustion processes but they could also be useful in exterior landfills.

Waste pyrolysis was used for alternative green energy production in the form of gaseous and liquid fuels (Chen et al. 2014a, b; Lam et al. 2016a). It was noted that pyrolysis was a thermal approach to treat solid waste without oxygen; however, it required higher working temperatures in the range of 300–650 °C, with the desired by-products being condensable gases and char. Furthermore, pyrolysis was carried out in an oxygen-free environment, and with inert gas purging (like nitrogen or others) used to maintain an inert atmosphere (Mahari et al. 2021). In addition, the liquid oil was improved via catalytic cracking, emulsification, deoxygenation, hydrocracking, and refinement or reforming so that it could be used as transportation fuel. Meanwhile, the gaseous products experienced reforming reactions for syngas production, and the solid product could be utilized as biochar or charcoal. During the pyrolysis process, the waste material was heated above its thermal stability threshold, causing the waste material components to break down and produce volatiles. The resulting volatile components were condensed into solid char, non-condensable gases, and liquid oil. Operating conditions and the feedstock had a considerable impact on the composition and production of gases or oils generated by the pyrolysis of waste. In most situations, the gas output for general waste increased along with working temperature but remained less than 1 Nm^3/kg waste (Chen et al. 2014a, b). Besides, the liquid products contained a large proportion of water with chemically complicated compounds. This necessitated sophisticated wastewater treatment processes prior to disposal, with insufficient outcomes in terms of energy or material cycling. Hence, plastic waste could be utilized in place of heterogeneous waste bulk if oil production was desired. Despite a high heating value and the promising resource for material or solid fuel of waste char (Sipra et al. 2018), it was polluted with harmful organic contaminants, and heavy metals needed more attention.

Typical pyrolysis methods which are heated by a furnace could yield potentially valuable liquid hydrocarbon fuels, but these approaches still have several drawbacks. In conventional pyrolysis, for example, uneven heat distribution has an impact on the heating process, extending the reaction time of pyrolysis. Furthermore, the resulting liquid oil possesses oxygen concentration, high acidity, and viscosity. As a result, the problem was in order to fulfill the demand for enhancing liquid oil for transporting grade fuel, which was driving research into the use of advanced pyrolysis techniques to enhance the conventional pyrolysis process (Mahari et al. 2021). Apart from that, the energy needed for the pyrolysis was provided by pyrolysis assisted with plasma; consequently, there was no requirement for energy from combustion to degrade waste materials. Syngas was created from the O, C, and H elements found in waste, obviating the requirement for utilizing oxidizing agents throughout the process (Muvhiiwa et al. 2018). There was a low tar content and high calorific value in the syngas created by plasma pyrolysis, making it suitable for use as a synthesis gas in order to produce hydrogen or in gas turbines to generate power (Punčochář et al. 2012). Additionally, vacuum pyrolysis was known as a novel method for transforming waste and biomass into liquid hydrocarbon fuels. The need for a carrier gas like argon or nitrogen to keep the atmosphere free of oxygen was removed in this method (Dewayanto et al. 2014; Fan et al. 2014). Besides, microwave pyrolysis was thought to be an exciting technology for energy recovery from hydrocarbon and biomass wastes (Lam et al. 2012; Abubakar et al. 2013). The temperature gradient inside the heated material between traditional heating and microwave made contributions to the distinct compositions and yields of products. This method of pyrolysis was observed to create a liquid oil free of sulfur with a calorific value of 46 MJ/kg which was comparable to 45 MJ/kg of diesel fuel as well as light C10–C15 hydrocarbons. Hence, pyrolysis of waste using a microwave could generate a high liquid oil output with desirable fuel properties (Lam et al. 2016b). In spite of the promising yield along with the fuel characteristics of the produced products, the thermochemical decomposition speed of this method was determined by the material's capability of absorbing microwave energy. As a result, microwave absorption enhancers were often used as supplementary supports during the microwave pyrolysis of materials with low absorption.

Torrefaction is a slower and milder kind of pyrolysis that has operating temperatures ranging between 200 and 350 °C with an overall focus on devolatilization and moisture evaporation. Normally, torrefaction produces char with a higher content of energy and enhanced stability (with no further degradation of microbes), in comparison with pyrolysis (Stępień and Białowiec 2018). Torrefaction is a more environmentally friendly and potential thermochemical technique that is commonly used by scientists to pre-treat various sorts of wastes. Torrefaction not only enhances thermochemical process performance (Abdulyekeen et al. 2021) but also promotes biomass hydrophobicity by decreasing moisture concentration, O/C and H/C proportions (Nhuchhen et al. 2021; Martinez et al. 2021), and enhancing fixed carbon. As a result, there was an increase in the energy density and calorific value of biomass (Sukiran et al. 2019; da Silva Ignacio et al. 2019). It was run in a nitrogen environment at a reaction temperature of 200–300 °C, a rate of heating of below 50 °C/min, and a residence period of 10–60 min (Zhang et al. 2020; Singh et al. 2020). Based on their room temperature condition, waste torrefaction products were classified into three types: solid, permanent or non-condensable gases, and liquid or condensable gases (Abdulyekeen et al. 2021). The solid contained char, significantly altered sugar structures, ash, newly produced polymer structures, as well as the original sugars' chaotic structure, and it was employed for the applications of bioenergy, adsorption, and soil amendment. Whereas, the liquid (unwanted product) containing lipids, organics, and reaction water, was utilized for (a) biogas generation through anaerobic digestion, (b) plant protection as herbicide, pesticide, and insecticide, and (c) phenol–formaldehyde adhesive synthesis in the plywood panel manufacturing process (Cahyanti et al. 2020). In addition, the gas was consisted of CO, CO_2, and traces of hydrogen and methane, which might be burned in the combustor for providing some of the energy needed for the torrefaction. Furthermore, char could be used as a high-quality fuel for remediating soil, co-firing in combustion, and adsorbing contaminants in water treatment (Nobre et al. 2019).

7.3.2 *Biological and Chemical Waste-to-Energy Technologies*

Waste valorization necessitates the integration of conversion methods in order to supply more opportunities for the generation of value-added products and power while lowering overall expenses. Hence, a number of the latest waste biorefinery technologies were attempted to combine with other approaches such as anaerobic digestion in order to provide parallel waste treatment as well as biotransformation to produce chemicals and biofuels (O'Callaghan 2016). Figure 7.4 described current methods of waste biorefinery.

Waste biorefinery processes rely mostly on single conversion technology, and they can be made from organic wastes with the use of rather simple biological methods. Multiple technologies are thus recommended to be combined for forming interconnected biorefinery process chains so that more commercial products can emerge. Furthermore, direct employment of heterogeneous waste is not only unusual but also unsuitable for biorefining, so according to the circular economy concept, it is evident that developing separate collecting systems along with recycling capacity should be a major priority. The reason is that separation technologies are necessary to remove antioxidants, cellulose, amino acids, and other undesirable compounds from

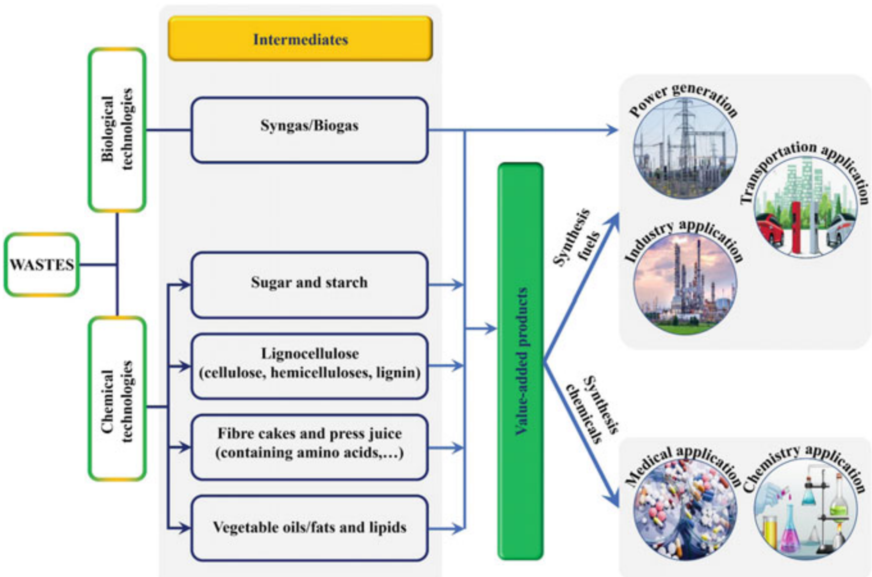

Fig. 7.4 Synthesis of platform chemicals from wastes (Fernando et al. 2006; Menon and Rao 2012)

the refinery process chain. While regular distillation can be employed in petroleum refineries to separate products, the chemical components that are recovered from biomass are observed to be less volatile. If waste is not effectively stored, the costs of substance separation could potentially exceed the value of the final bioproducts (Bastidas-Oyanedel and Schmidt 2018; Ashokkumar et al. 2019). Thus, in the bioeconomy, more intensive sorting of waste strategies as well as the development of appropriate procedures have to be prioritized.

The generation of bio-derived fuel from the use of waste material, among other WtE approaches, has the potential to be applied and constructed globally. For the creation of biofuel, various potential treatments were being investigated (Ali et al. 2020). Remarkably, in the United States, it was calculated to build a CHP facility aiming to process wastewater and produce bio-based fuel, thereby meeting the energy needs of more than 260,000 households. Biofuel was regarded as the most promising renewable energy source contender. It was expected to satisfy the aim of the Sustainable Development Goal in terms of renewable and eco-friendly sources of energy, as well as to help solve the global energy crisis (Acheampong et al. 2017; Bhan et al. 2020). There was a wide range of waste which could be used to generate bio-based fuel. The waste sources could be edible, like palm, corn, soya beans, or sugarcane; cellulosic biomass, including crop residue or wood sawdust, as well as waste from biological mass decomposition (Bilal and Iqbal 2020). Moreover, biomass could be utilized to produce a range of biofuels, including biohydrogen, biodiesel, biogas, and bioethanol (Pari et al. 2018). Biohydrogen, which could be produced both biologically and chemically, was another type of biofuel being studied as a possible replacement for fossil fuels. Attempts were being made to develop a promising bio-based process for biohydrogen production from waste contents rich in carbohydrates from the agriculture, food industries and timber (Gorazda et al. 2013). The chemical process by which lipids react with alcohol and a catalyst being present to form esters based on alkyl fatty acid is known as transesterification. The presence of fast and oil in sewage sludge made it more advantageous because they were a highly saturated lipids' excellent source such as triglycerides, monoglycerides, diglycerides, free fatty acids, and phospholipids (Kengpol et al. 2018; Jamal et al. 2022).

Anaerobic digestion was considered one of the least expensive means of energy production (Anukam et al. 2019). Biomethane or biogas generated through anaerobic digestion has been shown to be a renewable energy source (Materazzi and Foscolo 2019) that may be used not only to displace fossil fuels but also to produce energy (Hussain et al. 2020). In the anaerobic digestion process, organic components of waste such as crop residue, sewage sludge and garden waste were utilized as a substrate in anaerobic digestion, which was put in a closed reactor without oxygen, in which two important parameters in anaerobic digestion included temperature and pH (Li et al. 2015). Microbial activities predominated in the biogasification factory to break down organic waste and had four anaerobic digestion steps: acetogenesis, hydrolysis, methanogenesi, and sacidogenesis. Moreover, organic waste was broken down into protein, lipids and carbohydrates during the hydrolysis. Furthermore, they were transformed into sugars, monosaccharides, and amino acids during acidogenesis, which were further transformed into ammonia and volatile fatty acids during acetogenesis.

In the final stage of methanogenesis, it was observed that bacteria produced methane gas, which could be directly employed for fueling vehicles, cooking, or indirectly used for producing electricity (Pujara et al. 2020). After the biogasification process, the residual slurry could be utilized as manure to condition soil in activities related to agriculture. The microbial community responsible for generating biogas can be classed as thermophilic (50–65 °C) or mesophilic (25–37 °C), with higher operation temperatures generally increasing the speed of conversion in anaerobic digestion. The microbial decomposition processes in anaerobic digestion were quite similar to those in landfills; however, the anaerobic digestion system produced more biogas during a shorter reaction time. It was also demonstrated that anaerobic digestion is able to produce twice to four times the methane production per ton of waste just in three days compared to seven years in landfills (Gao et al. 2017). Furthermore, 1 m^3 of biogas was transformed into 6.7 kWh of energy with current technology (Hasan and Ammenberg 2019). Different process-engineering strategies such as pretreatment, additive dose, and process configuration could be in use depending on the kinds and quality of feedstock (for example, biodegradability, inhibitory components, nutritional content, and so on) (Safarudin et al. 2018; Meng et al. 2018). Anaerobic digestion was a critical process to activate a circular economy, which was especially true in the biological cycle, in which organic matter was treated in a sustainable manner and retained in a closed loop (Hussain et al. 2020). As a result, many problems including chemical fertilizers, waste in landfill, as well as nonrenewable energy could be handled. Actually, for decades, anaerobic digestion has been utilized, and technological advancements these days have resulted in its increasing applications in both developing and developed nations, on both large and small scales (Zhang et al. 2016). During the last twenty years, in Europe, the development of anaerobic digestion treatment capacity has been primarily affected by the policies of the EU, particularly the ones focusing on waste management and prevention, including biodegradable materials' disposal. Its goal was to alleviate climate change while also enriching deteriorated soil (Gregson et al. 2015).

Biogas produced by anaerobic digestion was frequently used to generate electricity or was directly flared in some cases while the value and extent of biogas applications could be greatly enhanced by the removal of CO_2 and other pollutant gases so as to supply biomethane with high quality as an alternative for natural gas in various domestic purposes and industrial uses (Sahota et al. 2018; Srinuanpan et al. 2019). However, biogas from anaerobic digestion cannot be considered as a sustainable energy source without the addition of solar energy or wind power. Anaerobic digestion possessed multi-functionality such as the most obvious strength, reinforcing sustainability principles with ties to numerous breakthrough waste refinery techniques and sustainable agriculture so that waste concerns could be alleviated and nutrient recycling worldwide could be handled. According to recent studies, the critical issue in anaerobic digestion and the bio-economy was to pave the way for the next wave of evolutions that might promote technology and bio-origin products for promoting more sustainable and transformative organic waste treatment.

7.3.3 Refuse-Derived Fuel

Refuse-derived fuel is the non-recyclable combustible part with a high calorific of treated waste that can be used as a fuel for producing electricity and steam or employed as an alternative fuel in boilers and industrial furnaces. As a result, particular industrial wastes including sewage sludge, textile waste, plastics, agriculture waste, spent oil, wood cuttings, and scrap papers can be employed in WtE facilities alongside refuse-derived fuel to improve the calorific value. Notably, the refuse-derived fuel process involves separating non-combustible wastes such as metals, glass, sand, stones, and so on, and then the remaining dried waste would be crushed to raise its surface area. Finally, the waste can be directly utilized as boiler feed or processed into pellets if necessary. In the last decade, the creation of fuel from waste in WtE facilities contributed to a 50% decrease in the waste that was transported to landfills (Brew 2020). Aside from wealthy nations, the concern about recovering refuse-derived fuel from waste has spread to some developing countries, including Indonesia, Thailand, and India. Furthermore, refuse-derived fuel is also gaining popularity in the Middle East. Despite being the world's second-biggest producer of gas, the Kingdom of Saudi Arabia initiated research into refuse-originated fuel from municipal solid waste as a promising renewable source of energy (Yang et al. 2021). Figure 7.5 depicted the refuse-derived fuel synthesis from waste. The physical characteristics of optimum refuse-derived fuel included particle size (ranging from 10 to 300 mm), moisture concentration (between 10 and 30%), and bulk density (120–300 kg/m^3). In addition, the ideal calorific value was more than 2,000 kcal/kg with a volatile matter of 75–80% and ash concentration of 10–20% (Akdağ et al. 2016). A lower concentration of moisture along with greater calorific values was desired for a cost-effective and beneficial WtE refuse-derived fuel factory (Vounatsos et al. 2015), while sulphur, heavy metals, and chlorine were not (Psomopoulos 2014).

In general, refuse-derived fuel is seen as a sustainable fuel that mitigates environmental impacts and supports natural resource conservation such as coal, natural gas, and petroleum. The refuse-originated fuel produced was often utilized as a coal alternative in the industry of cement to reduce CO_2 emissions by 40% (Rodrigues and Joekes 2011). Nonetheless, significant attempts should be made to develop novel technologies and enhance existing techniques in order to achieve higher fuel quality and profit margins.

7.4 Barriers to WtE Technologies

Barriers often prevent organizations from developing technologies and processes which are critical for green-supply chains in order to convert energy from waste. The key economic constraints, according to both intermediaries and developers, are related to economic viability, virgin material prices as well as the functionality of

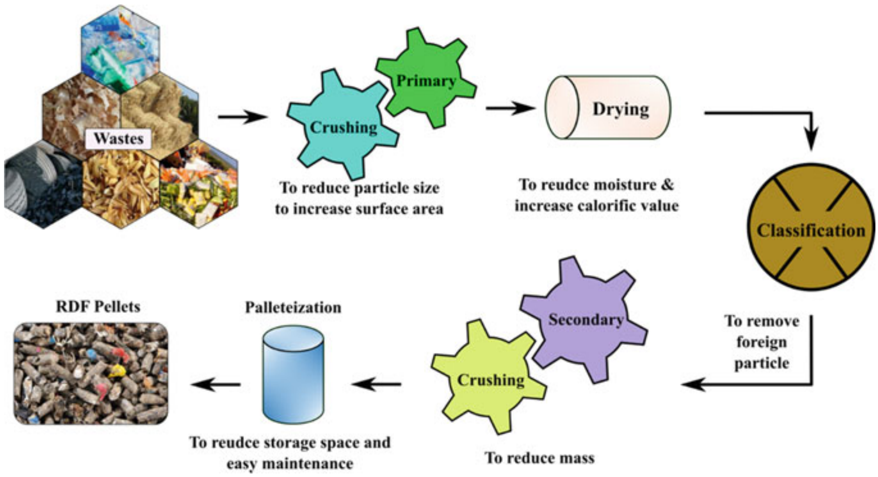

Fig. 7.5 Refuse-derived fuel preparation from waste (Pujara et al. 2020)

the recyclables market. Collection expenses are prohibitively expensive, the materials obtained are insufficiently useful, or their prices are excessively fluctuating. Furthermore, developing markets for secondary materials were shown to provide substantial challenges for biogas actors that used biodegradable waste. Besides, developers raised concerns about losing not only economic but also environmental advantages due to inefficient waste collection logistics. The difficulties associated with a shortage of regional or governmental support, like economic incentives to encourage secondary material markets or directly support funding for R&D activities, were highlighted by intermediaries. Moreover, policymakers faced challenges in developing or implementing green policy chains that could bring benefits to the whole society. Apart from that, the identified barriers differed significantly across intermediaries and developers. In comparison with intermediaries, developers assessed regulatory and institutional impediments as less important. In particular, many intermediaries showed concern about how various rules could restrain the circular economy. Nonetheless, the change of legislation, notably the divided obligations in waste management, was the primary concern of not only developers but also intermediaries. As a result of farmers' concerns about the economics and dependability of farm-scale biogas facilities, the use of waste-derived products as fertilizers has been restricted. Generally, outdated habits and thoughts were hindering the transition to circular processes in every sector. Apart from the aforementioned restrictions, there existed certain technological challenges. Some local industries and firms lacked access to green techniques and remained reliant on conformist methods, which was especially visible in developing countries. If the above-mentioned hurdles were not overcome, climate change, biodiversity loss, and other ecological problems would occur.

7.5 Conclusions

The precipitous rise in global population led to significant urbanization, and thus an unprecedented rise in waste material. Cities were unsustainable due to their abnormally high waste levels. These wastes, on the other hand, represented a rich supply of energy that could be regenerated as a renewable source of energy. Therefore, the supply chain of WtE for the energy system was considered a significant stage for the industrial circular economy in tackling the existing difficulties of energy demand, waste management for the communities in the world, and greenhouse gas emissions. Generally, if WtE technologies were implemented, waste could be regarded as one of the most promising renewable sources of energy as these methods would both alleviate reliance on traditional energy sources in order to meet the ever-increasing demand for energy, but they would also mitigate the waste problem. According to the available WtE techniques, the most viable waste resolutions in developing nations were anaerobic digestion for organic wastes, landfilling for inert wastes, incineration for the mixture of waste, gasification, and pyrolysis for certain waste types. On the other hand, regulations and rules of the governments, advanced technology as well as financial support could improve the future outlook for WtE facilities.

References

Abdulyekeen KA, Umar AA, Patah MFA, Daud WMAW (2021) Torrefaction of biomass: production of enhanced solid biofuel from municipal solid waste and other types of biomass. Renew Sustain Energy Rev 150:111436

Abubakar Z, Salema AA, Ani FN (2013) A new technique to pyrolyse biomass in a microwave system: effect of stirrer speed. Bioresour Technol 128:578–585

Acheampong M, Ertem FC, Kappler B, Neubauer P (2017) In pursuit of sustainable development goal (SDG) number 7: will biofuels be reliable? Renew Sustain Energy Rev 75:927–937

Akdağ AS, Atımtay A, Sanin FD (2016) Comparison of fuel value and combustion characteristics of two different RDF samples. Waste Manag 47:217–224

Ali J, Rasheed T, Afreen M, Anwar MT, Nawaz Z, Anwar H, Rizwan K (2020) Modalities for conversion of waste to energy—challenges and perspectives. Sci Total Environ 727:138610

Anukam A, Mohammadi A, Naqvi M, Granström K (2019) A review of the chemistry of anaerobic digestion: methods of accelerating and optimizing process efficiency. Processes 7:504. https://doi.org/10.3390/pr7080504

Arena U (2015) From waste-to-energy to waste-to-resources: the new role of thermal treatments of solid waste in the recycling society. Waste Manag (New York, NY) 37:1–2

Ashokkumar V, Chen W-H, Ngamcharussrivichai C, Agila E, Ani FN (2019) Potential of sustainable bioenergy production from *Synechocystis* sp. cultivated in wastewater at large scale—a low cost biorefinery approach. Energy Convers Manag 186:188–199

Astrup TF, Tonini D, Turconi R, Boldrin A (2015) Life cycle assessment of thermal waste-to-energy technologies: review and recommendations. Waste Manag 37:104–115

Balaman ŞY, Wright DG, Scott J, Matopoulos A (2018) Network design and technology management for waste to energy production: an integrated optimization framework under the principles of circular economy. Energy 143:911–933

Bastidas-Oyanedel JR, Schmidt JE (2018) Increasing profits in food waste biorefinery-a techno-economic analysis. Energies 11. https://doi.org/10.3390/en11061551

Bernstad A, la Cour Jansen J, Aspegren H (2012) Local strategies for efficient management of solid household waste–the full-scale Augustenborg experiment. Waste Manag Res 30:200–212
Bhan C, Verma L, Singh J (2020) Alternative fuels for sustainable development. In: Environmental concerns and sustainable development. Springer, pp 317–331
Bilal M, Iqbal H (2020) Ligninolytic enzymes mediated ligninolysis: an untapped biocatalytic potential to deconstruct lignocellulosic molecules in a sustainable manner. Catal Lett 150:524–543
Boloy RAM, da Cunha Reis A, Rios EM, de Araújo Santos Martins J, Soares LO, de Sá Machado VA, de Moraes DR (2021) Waste-to-energy technologies towards circular economy: a systematic literature review and bibliometric analysis. Water Air Soil Pollut 232:1–25
Bosmans A, Vanderreydt I, Geysen D, Helsen L (2013) The crucial role of waste-to-energy technologies in enhanced landfill mining: a technology review. J Clean Prod 55:10–23
Brew M (2020) What's on the horizon for refuse-derived fuel as brexit looms and production evolves
Cahyanti MN, Doddapaneni TRKC, Kikas T (2020) Biomass torrefaction: an overview on process parameters, economic and environmental aspects and recent advancements. Bioresour Technol 301:122737
Chen D, Yin L, Wang H, He P (2018) Reprint of pyrolysis technologies for municipal solid waste: a review Pyrolysis technologies for municipal solid waste: a review. Waste Manag (January)
Chen D, Yin L, Wang H, He P (2014a) Pyrolysis technologies for municipal solid waste: a review. Waste Manag 34:2466–2486
Chen G, Liu C, Ma W, Zhang X, Li Y, Yan B, Zhou W (2014b) Co-pyrolysis of corn cob and waste cooking oil in a fixed bed. Bioresour Technol 166:500–507
Cui C, Liu Y, Xia B, Jiang X, Skitmore M (2020) Overview of public-private partnerships in the waste-to-energy incineration industry in China: status, opportunities, and challenges. Energy Strateg Rev 32:100584
da Silva Ignacio LH, de Almeida Santos PE, Duarte CAR (2019) An experimental assessment of Eucalyptus urosemente energy potential for biomass production in Brazil. Renew Sustain Energy Rev 103:361–369
De Greef J, Verbinnen B, Van Caneghem J (2018) Waste-to-energy: coupling waste treatment to highly efficient CHP. Int J Chem React Eng 16
Deng N, Zhang A, Zhang Q, He G, Cui W, Chen G, Song C (2017) Simulation analysis and ternary diagram of municipal solid waste pyrolysis and gasification based on the equilibrium model. Bioresour Technol 235:371–379
Dewayanto N, Isha R, Nordin MR (2014) Use of palm oil decanter cake as a new substrate for the production of bio-oil by vacuum pyrolysis. Energy Convers Manag 86:226–232
Dong J, Tang Y, Nzihou A, Chi Y (2019) Key factors influencing the environmental performance of pyrolysis, gasification and incineration waste-to-energy technologies. Energy Convers Manag 196:497–512
Fan Y, Cai Y, Li X, Yu N, Yin H (2014) Catalytic upgrading of pyrolytic vapors from the vacuum pyrolysis of rape straw over nanocrystalline HZSM-5 zeolite in a two-stage fixed-bed reactor. J Anal Appl Pyrolysis 108:185–195
Fernando S, Adhikari S, Chandrapal C, Murali N (2006) Biorefineries: current status, challenges, and future direction. Energy Fuels 20:1727–1737
Gañan J, Abdulla AA-K, Miranda AB, Turegano J, Correia S, Cuerda EM (2005) Energy production by means of gasification process of residuals sourced in Extremadura (Spain). Renew Energy 30:1759–1769
Gao A, Tian Z, Wang Z, Wennersten R, Sun Q (2017) Comparison between the technologies for food waste treatment. Energy Procedia 105:3915–3921
Gorazda K, Wzorek Z, Tarko B, Nowak AK, Kulczycka J, Henclik A (2013) Phosphorus cycle-possibilities for its rebuilding. Acta Biochim Pol 60
Gregson N, Crang M, Fuller S, Holmes H (2015) Interrogating the circular economy: the moral economy of resource recovery in the EU. Econ Soc 44:218–243

Hasan ASMM, Ammenberg J (2019) Biogas potential from municipal and agricultural residual biomass for power generation in Hazaribagh, Bangladesh—a strategy to improve the energy system. Renew Energy Focus 29:14–23

Hussain Z, Mishra J, Vanacore E (2020) Waste to energy and circular economy: the case of anaerobic digestion. J Enterp Inf Manag 33:817–838

ISWA (2018) China's ban on recyclables: beyond the obvious [WWW Document]. https://nerc.org/news-and-updates/blog/nerc-blog/2018/01/23/chinas-ban-on-recyclables. Accessed 15 July 2022

Jamal Y, Shah IH, Park H-S (2022) Mono-alkyl esters (biodiesel) production from wastewater sludge by esterification. Biofuels 13:351–357

Jeswani HK, Azapagic A (2016) Assessing the environmental sustainability of energy recovery from municipal solid waste in the UK. Waste Manag 50:346–363

Kahle K, Kamuk B, Kallesøe J, Fleck E, Lamers F, Jacobsson L, Sahlén J (2015) Bottom ash from WTE plants: metal recovery and utilization. Ramböll, Copenhagen

Kengpol A, Choi GH, Poompipatpong C (2018) A decision support methodology for using alternative fuel in diesel engine. Eng J 22

Kirchherr J, Reike D, Hekkert M (2017) Conceptualizing the circular economy: an analysis of 114 definitions. Resour Conserv Recycl 127:221–232

Lam SS, Russell AD, Lee CL, Chase HA (2012) Microwave-heated pyrolysis of waste automotive engine oil: influence of operation parameters on the yield, composition, and fuel properties of pyrolysis oil. Fuel 92:327–339

Lam SS, Liew RK, Jusoh A, Chong CT, Ani FN, Chase HA (2016a) Progress in waste oil to sustainable energy, with emphasis on pyrolysis techniques. Renew Sustain Energy Rev 53:741–753

Lam SS, Mahari WAW, Cheng CK, Omar R, Chong CT, Chase HA (2016b) Recovery of diesel-like fuel from waste palm oil by pyrolysis using a microwave heated bed of activated carbon. Energy 115:791–799

Li Y-F, Nelson MC, Chen P-H, Graf J, Li Y, Yu Z (2015) Comparison of the microbial communities in solid-state anaerobic digestion (SS-AD) reactors operated at mesophilic and thermophilic temperatures. Appl Microbiol Biotechnol 99:969–980

Lu J-W, Zhang S, Hai J, Lei M (2017) Status and perspectives of municipal solid waste incineration in China: a comparison with developed regions. Waste Manag 69:170–186. https://doi.org/10.1016/j.wasman.2017.04.014

Mahari WAW, Azwar E, Foong SY, Ahmed A, Peng W, Tabatabaei M, Aghbashlo M, Park Y-K, Sonne C, Lam SS (2021) Valorization of municipal wastes using co-pyrolysis for green energy production, energy security, and environmental sustainability: a review. Chem Eng J 421:129749

Makarichi L, Jutidamrongphan W, Techato K (2018) The evolution of waste-to-energy incineration: a review. Renew Sustain Energy Rev 91:812–821

Malinauskaite J, Jouhara H, Czajczyńska D, Stanchev P, Katsou E, Rostkowski P, Thorne RJ, Colón J, Ponsá S, Al-Mansour F, Anguilano L, Krzyżyńska R, López IC, Vlasopoulos A, Spencer N (2017) Municipal solid waste management and waste-to-energy in the context of a circular economy and energy recycling in Europe. Energy 141:2013–2044. https://doi.org/10.1016/j.energy.2017.11.128

Malindzakova M, Straka M, Rosova A, Kanuchova M, Trebuna P (2015) Modeling the process for incineration of municipal waste. Przem Chem 94:1260–1264

Malla FA, Mushtaq A, Bandh SA, Qayoom I, Hoang AT (2022) Understanding climate change: scientific opinion and public perspective. In: Climate change. Springer, pp 1–20

Martinez CLM, Saari J, Melo Y, Cardoso M, de Almeida GM, Vakkilainen E (2021) Evaluation of thermochemical routes for the valorization of solid coffee residues to produce biofuels: a Brazilian case. Renew Sustain Energy Rev 137:110585

Materazzi M, Foscolo PU (2019) The role of waste and renewable gas to decarbonize the energy sector. In: Substitute natural gas from waste. Elsevier, pp 1–19. https://doi.org/10.1016/B978-0-12-815554-7.00001-5

Mayer F, Bhandari R, Gäth S (2019) Critical review on life cycle assessment of conventional and innovative waste-to-energy technologies. Sci Total Environ 672:708–721
McKendry P (2002) Energy production from biomass (part 3): gasification technologies. Bioresour Technol 83:55–63. https://doi.org/10.1016/S0960-8524(01)00120-1
Mehta A, Mishra A, Basu S, Shetti NP, Reddy KR, Saleh TA, Aminabhavi TM (2019) Band gap tuning and surface modification of carbon dots for sustainable environmental remediation and photocatalytic hydrogen production—a review. J Environ Manage 250:109486
Meng X, Yu D, Wei Y, Zhang Y, Zhang Q, Wang Z, Liu J, Wang Y (2018) Endogenous ternary pH buffer system with ammonia-carbonates-VFAs in high solid anaerobic digestion of swine manure: an alternative for alleviating ammonia inhibition? Process Biochem 69:144–152
Menon V, Rao M (2012) Trends in bioconversion of lignocellulose: biofuels, platform chemicals & biorefinery concept. Prog Energy Combust Sci 38:522–550
Michaels T (2014) The 2014 ERC directory of waste-to-energy facilities. Energy Recover Counc
Mishra A, Shetti NP, Basu S, Raghava Reddy K, Aminabhavi TM (2019) Carbon cloth-based hybrid materials as flexible electrochemical supercapacitors. ChemElectroChem 6:5771–5786
Muvhiiwa RF, Sempuga B, Hildebrandt D, Van Der Walt J (2018) Study of the effects of temperature on syngas composition from pyrolysis of wood pellets using a nitrogen plasma torch reactor. J Anal Appl Pyrolysis. https://doi.org/10.1016/j.jaap.2018.01.014
Nhuchhen DR, Afzal MT, Parvez AM (2021) Effect of torrefaction on the fuel characteristics of timothy hay. Biofuels 12:391–404. https://doi.org/10.1080/17597269.2018.1479135
Nobre C, Alves O, Longo A, Vilarinho C, Gonçalves M (2019) Torrefaction and carbonization of refuse derived fuel: char characterization and evaluation of gaseous and liquid emissions. Bioresour Technol 285:121325
O'Callaghan K (2016) Technologies for the utilisation of biogenic waste in the bioeconomy. Food Chem 198:2–11
Pari L, Suardi A, Del Giudice A, Scarfone A, Santangelo E (2018) Influence of chipping system on chipper performance and wood chip particle size obtained from peach prunings. Biomass Bioenerg 112:121–127
Persson U, Münster M (2016) Current and future prospects for heat recovery from waste in European district heating systems: a literature and data review. Energy. https://doi.org/10.1016/j.energy.2015.12.074
Psomopoulos CS (2014) Residue derived fuels as an alternative fuel for the Hellenic power generation sector and their potential for emissions reduction. AIMS Energy 2:321–341
Pujara Y, Govani J, Chabhadiya K, Patel H, Vaishnav K, Pathak P (2020) Waste-to-energy: suitable approaches for developing countries. Altern Energy Resour 173–191
Punčochář M, Ruj B, Chatterj PK (2012) Development of process for disposal of plastic waste using plasma pyrolysis technology and option for energy recovery. Procedia Eng 42:420–430
Qi T, Lei T, Yan B, Chen G, Li Z, Fatehi H, Wang Z, Bai X-S (2019) Biomass steam gasification in bubbling fluidized bed for higher-H2 syngas: CFD simulation with coarse grain model. Int J Hydrogen Energy 44:6448–6460
Rauch R, Hofbauer H, Neuling U, Kaltschmitt M (2018) Biokerosene production from biochemical and thermo-chemical biomass conversion and subsequent Fischer-Tropsch synthesis. In: Biokerosene. Springer, pp 497–542
Rodrigues FA, Joekes I (2011) Cement industry: sustainability, challenges and perspectives. Environ Chem Lett 9:151–166. https://doi.org/10.1007/s10311-010-0302-2
Safarudin A, Millati R, Taherzadeh MJ, Niklasson C (2018) Inhibition of patchouli oil for anaerobic digestion and enhancement in methane production using reverse membrane bioreactors. Renew Energy 129:748–753
Saghir M, Rehan M, Nizami A-S (2018) Recent trends in gasification based waste-to-energy. Gasif Low-Grade Feed 97–113
Sahota S, Shah G, Ghosh P, Kapoor R, Sengupta S, Singh P, Vijay V, Sahay A, Vijay VK, Thakur IS (2018) Review of trends in biogas upgradation technologies and future perspectives. Bioresour Technol Rep 1:79–88

Sanlisoy A, Carpinlioglu MO (2017) A review on plasma gasification for solid waste disposal. Int J Hydrogen Energy 42:1361–1365

Seo Y-C, Alam MT, Yang W-S (2018) Gasification of municipal solid waste. Gasif Low-Grade Feed

Sharma S, Basu S, Shetti NP, Aminabhavi TM (2020a) Waste-to-energy nexus for circular economy and environmental protection: recent trends in hydrogen energy. Sci Total Environ 713:136633

Sharma S, Basu S, Shetti NP, Kamali M, Walvekar P, Aminabhavi TM (2020b) Waste-to-energy nexus: a sustainable development. Environ Pollut 267:115501

Singh RK, Sarkar A, Chakraborty JP (2020) Effect of torrefaction on the physicochemical properties of eucalyptus derived biofuels: estimation of kinetic parameters and optimizing torrefaction using response surface methodology (RSM). Energy 198:117369

Sipra AT, Gao N, Sarwar H (2018) Municipal solid waste (MSW) pyrolysis for bio-fuel production: a review of effects of MSW components and catalysts. Fuel Process Technol 175:131–147. https://doi.org/10.1016/j.fuproc.2018.02.012

Srinuanpan S, Cheirsilp B, Boonsawang P, Prasertsan P (2019) Immobilized oleaginous microalgae as effective two-phase purify unit for biogas and anaerobic digester effluent coupling with lipid production. Bioresour Technol 281:149–157

Stępień P, Białowiec A (2018) Kinetic parameters of torrefaction process of alternative fuel produced from municipal solid waste and characteristic of carbonized refuse derived fuel. Detritus 3:75–83

Sukiran MA, Abnisa F, Daud WMAW, Bakar NA, Aziz AA, Loh SK (2019) Upgrading of oil palm biomass by torrefaction process: a preliminary study. AIP Conf Proc 2168:020059. https://doi.org/10.1063/1.5132486

Suthar S, Rayal P, Ahada CPS (2016) Role of different stakeholders in trading of reusable/recyclable urban solid waste materials: a case study. Sustain Cities Soc 22:104–115

Suzuki S (2007) The Ebara advanced fluidization process for energy recovery and ash vitrification in 15th North American waste to energy conference, Miami, Florida, USA, pp 11–12

Themelis NJ, Ma W (2021) Waste to energy (WTE) in China: from latecomer to front runner. Waste Dispos Sustain Energy 3:267–274

Tomić T, Schneider DR (2018) The role of energy from waste in circular economy and closing the loop concept–energy analysis approach. Renew Sustain Energy Rev 98:268–287

Tomić T, Dominković DF, Pfeifer A, Schneider DR, Pedersen AS, Duić N (2017) Waste to energy plant operation under the influence of market and legislation conditioned changes. Energy 137:1119–1129

Tsui T-H, Wong JWC (2019) A critical review: emerging bioeconomy and waste-to-energy technologies for sustainable municipal solid waste management. Waste Dispos Sustain Energy 1:151–167

UNDESA (2018) UN DESA begins a new partnership to explore sustainable water and energy solutions [WWW Document]. https://www.un.org/development/desa/capacity-development/2018/03/12/un-desa-beginsnew-partnership-to-explore-sustainable-water-and-energy-solutions/. Accessed 15 Aug 2022

Van Caneghem J, Verbinnen B, Cornelis G, de Wijs J, Mulder R, Billen P, Vandecasteele C (2016) Immobilization of antimony in waste-to-energy bottom ash by addition of calcium and iron containing additives. Waste Manag 54:162–168

Van Caneghem J, Van Acker K, De Greef J, Wauters G, Vandecasteele C (2019) Waste-to-energy is compatible and complementary with recycling in the circular economy. Clean Technol Environ Policy 21:925–939

Verbinnen B, Billen P, Van Caneghem J, Vandecasteele C (2017) Recycling of MSWI bottom ash: a review of chemical barriers, engineering applications and treatment technologies. Waste Biomass Valorization 8:1453–1466

Vounatsos P, Agraniotis M, Grammelis P, Kakaras E, Skiadi O, Zarmpoutis T (2015) Refuse-derived fuel classification in a mechanical–biological treatment plant and its valorization with techno-economic criteria. Int J Environ Sci Technol 12:1137–1146

Win MM, Asari M, Hayakawa R, Hosoda H, Yano J, Sakai S (2019) Characteristics of gas from the fluidized bed gasification of refuse paper and plastic fuel (RPF) and wood biomass. Waste Manag 87:173–182

Xiao H, Li Z, Jia X, Ren J (2020) Waste to energy in a circular economy approach for better sustainability: a comprehensive review and SWOT analysis. Waste-to-Energy 23–43

Yang Y, Liew RK, Tamothran AM, Foong SY, Yek PNY, Chia PW, Van Tran T, Peng W, Lam SS (2021) Gasification of refuse-derived fuel from municipal solid waste for energy production: a review. Environ Chem Lett 1–14

Zhang Q, Hu J, Lee D-J (2016) Biogas from anaerobic digestion processes: research updates. Renew Energy 98:108–119. https://doi.org/10.1016/j.renene.2016.02.029

Zhang S, Su Y, Xiong Y, Zhang H (2020) Physicochemical structure and reactivity of char from torrefied rice husk: effects of inorganic species and torrefaction temperature. Fuel 262:116667