Chapter 10
Waste-to-Energy: Applications and Perspectives on Sustainable Aviation Fuel Production

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Abstract Global climate change and depletion of resources are crucial issues for modern societies. Moreover, population growth and rapid industrialization result in increased energy demand. To meet ongoing energy demand, developed and developing countries must adopt sustainable waste management methods. In addition to prevention and recycling, waste-to-energy technologies could certainly be beneficial. Except for heat and electricity generation, biofuels can also be produced from waste. Aviation sector is expanding and its greenhouse gas emissions account for about 2% of total global emissions. Aircraft emissions are more persistent in higher altitudes having a greater environmental impact. Hence, decarbonization of the sector is an ongoing challenge. Sustainable aviation fuels comprise a promising solution over the following years. Utilization of waste materials will contribute to the total production of biojet fuels. To date, eight pathways have been certified by the American Society for Testing Materials standards for blending limits up to 50% with conventional jet fuels. The current chapter highlights sustainable waste management methods focused on waste-to-energy conversion technologies for biojet fuel production from waste materials as feedstocks. Current conversion pathways are further analyzed and discussed toward a "greener" and more sustainable future of aviation industry. Hydrotreated esters and fatty acids pathway is the most mature and promising production method for oleochemical feedstocks, including waste oils. Thermochemical methods and alcohol-to-jet pathway will contribute to biojet fuel production in the following years.

Keywords Waste-to-energy · Biofuels · Biojet · Decarbonization · GHG emissions · Sustainable aviation fuels · Sustainable waste management

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P. C. Shukla et al. (eds.), *Renewable Fuels for Sustainable Mobility*, Energy, Environment, and Sustainability, https://doi.org/10.1007/978-981-99-1392-3_10

10.1 Introduction

Rapid growth in population and urbanization resulted in higher energy needs and faster consumption of goods. The enormous generation of waste is a crucial environmental concern. Sustainable waste management and energy recovery from waste can minimize environmental pollution and simultaneously promote the energy sector for the production of renewable fuels to meet future energy demand (Brunner and Rechberger 2015; Khan and Kabir 2020).

Waste-to-energy (WtE) technologies include several methods such as incineration, pyrolysis, gasification, fermentation, anaerobic digestion, landfill, and others (Kumar and Ankaram 2019). During the last decades, WtE technologies have undergone rapid development. Different waste management policies and strategies exist around the globe between developing and developed countries (Sun, et al. 2020). Current situation regarding municipal solid waste (MSW) management needs strengthening, especially in developing countries. Major challenges involve improper separation of MSW, lack of advanced technologies, and limited recycling (Shah, et al. 2021).

European targets for sustainable waste management involve the principles of circular economy in terms of renewable energy utilization, energy efficiency improvement, and reduction of dependency on imported sources. Three main policies are included in WtE multi-purpose concept: waste management, energy union, and air quality/climate change (Malinauskaite and Jouhara 2019).

Energy needs in the transportation sector will continue to grow over the next decades. Aviation sector comprises one of the fast-growing transport sectors with a large contribution to the global economy. However, sector's greenhouse gas (GHG) emissions reach approximately 2% in global emissions (Reaching 2021). Aircraft emissions include carbon dioxide (CO_2), water vapor (H_2O), nitrogen oxides (NO_x), carbon monoxide (CO), sulfur oxides (SO_x), soot, and particles. Aviation emissions affect climate change through radiative forcing (RF) and the effects are interconnected and depend on the altitude where they are emitted. Long-term impacts are associated with CO_2 emissions, whereas short-term impacts are related to non-CO_2 emissions. Chemical and particle microphysical properties of the upper atmosphere are affected by aviation emissions and cloud effects, causing warming or cooling (Hashemi Devin and Sabziparvar 2002). In the troposphere, pollutants can be removed, due to water vapor precipitation. On the contrary, the stratosphere, which lies above the atmosphere, lacks water vapors and pollutants remain for years. The exact height of the thin layer between troposphere and stratosphere (tropopause) is affected by several factors including latitude, weather, temperature, and human activity (Sheng et al. 2015).

Decarbonization of aviation sector is a crucial challenge in order to achieve early reduction of emissions by 2030 and deeper ones by 2050 (Reaching 2021; Abrantes 2050). Despite the relatively low contribution of aviation sector to total CO_2 emissions, reducing CO_2 emissions is essential according to the aviation industry's growth projections. In Europe, expected CO_2 emissions will reach 360 million tons by 2023, while fuel demand will amount to 118 Mtoe at the same time (Kousoulidou and Lonza

2016). Toward this direction, sustainable aviation fuels (SAF) present the most viable solution in near future compared to other options such as hydrogen and electrification (Bauen et al. 2020).

In the ground transport sector, in 1894, Rudolf Diesel's self-igniting engine invention quickly rose to prominence in the ground transportation industry. Diesel engines are more efficient, because they have a higher compression ratio and operate with a leaner mixture. However, since stringent regulations have been introduced to control and reduce diesel engine emissions, alternative fuels, such as biodiesel, bio-alcohols, biogas, and bio-oil, need to be developed (Vijayashree and Ganesan 2020). CO_2 reduction of compression ignition engines can be further improved by advanced combustion technologies combined with alternative fuels, such as alcohol fuels (methanol, ethanol). The charge cooling effect lowers the combustion temperature and increases overall efficiency. Moreover, alcohol–diesel fuel blends can reduce particulate matter (PM) and soot emissions (Shamun et al. 2020).

In the air transport sector, military and commercial aircraft engines are mostly powered by gas turbine engines. Despite the fact that gas turbine engines are very efficient, replacement of kerosene-based fuels is essential for the fulfillment of future energy demand needs and mitigating climate change. In order to be compatible with existing aircraft engines, biojet fuels have to meet strict specifications according to American Society for Testing and Materials (ASTM) D7566 standard. Performance characteristics of biojet fuels include low-temperature fluidity, thermal oxidation stability, combustion characteristics, compatibility with current aviation fueling system, fuel volatility, fuel metering, and aircraft range (Chandralingam 2020; Yang et al. 2019). Aircraft fuel efficiency has improved substantially over the last decades and is expected to improve further in the future. Synthetic jet fuels produced by coal or natural gas through Fischer–Tropsch synthesis are not considered sustainable. However, coal-to-liquid (CTL), gas-to-liquid (GTL), and other first-generation synthetic fuels paved the way for biomass-to-liquid biofuels. Alternatives to food plant-derived fuels are the focus of ongoing research in the world. Nevertheless, almost all alternative fuels face implementation challenges compared to kerosene fuels. High energy content per unit of weight and volume is a basic requirement for aircraft fuels. Hydrogen (H_2) may not emit CO_2 and it is also lightweight, but production, handling, infrastructure, and storage are the main drawbacks (Daggett et al. 2006; Marsh 2008).

Utilization of waste materials for biofuel production, including SAF, is of great significance for a sustainable future of aviation industry. In industrialized countries, waste materials such as MSW, forestry, and agricultural residues are considered as renewable feedstock with a high potential to recover energy through different WtE technologies (Sindhu et al. 2019; Montoya Sánchez et al. 2022). In Fig. 10.1, an illustrative flowchart connecting waste generation and its utilization for energy recovery in the fast-growing aviation sector is shown.

Hydroprocessing of oleochemical/lipid feedstocks or Hydroprocessed Esters and Fatty Acids (HEFA) pathway is the most widely used technology for SAF production. Currently, this is the only fully commercialized method. Nevertheless, future demand is not going to be fulfilled only from these kinds of feedstocks, but lignocellulosic

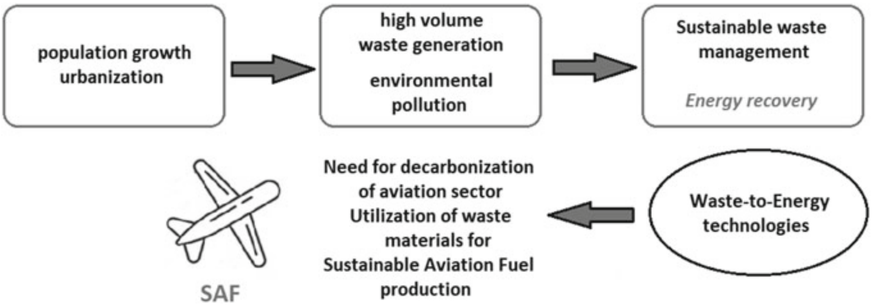

Fig. 10.1 Waste generation and utilization as feedstock through WtE technologies for SAF production

residues and MSW could contribute to aviation biofuel production (Zhang, et al. 2022; Monteiro, et al. 2022).

Catalytic conversion of alcohols as intermediate (alcohol-to-jet) technology as well as thermochemical methods, such as gasification-Fischer-Tropsch synthesis, are rising in technological readiness level. However, techno-economic models reveal that without policy support measurements, none of the approved pathways could be economically viable. Financial viability could be possible through the cumulative impact of multiple policies (Dahal 2021; Machineni 2019; Launay et al. 1998). Biofuels are evaluated against the broader sustainability claims that include: (a) climate security and appropriate land use, (b) social issues, (c) economic viability in existing sustainable environment, (d) technological advances combined with sustainable standards, and (e) governments encouraging plans to provide a smooth legislative agenda (Thangaraja et al. 2020).

10.2 Historical Overview—Environmental Legislation

First attempts on solid waste management in Western cultures date back to Greek Era in 500 BC. Municipal dumps had been organized in order to prevent garbage throwing in the streets. Similarly, European and American cities adopted primitive methods in the nineteenth century for the disposal of waste such as landfilling, burning, or utilization as fertilizers (Louis 2004). In the United States, the Federal Congress in 1970 legislated comprehensive laws for solid waste planning, energy conservation, recycling, etc. (Kovacs 1993).

Rapid urbanization and humans' population growth resulted in a rapid increase of MSW. Responsible authorities were pushed in order to take action and develop new strategies. There was realization that landfilling could not be efficient. First MSW incinerators without energy recovery were constructed in UK and US in 1970 and 1885, respectively. Hence, since the late nineteenth century, the development of MSW incinerators has been significant. Volumetric reduction of waste, optimal heat, and materials recovery and prevention of emissions were the main targets for successful implementation of incinerators (Makarichi et al. 2018).

In fact, utilization of energy was introduced as a technical requirement, when air pollution started to be systematically controlled. Meanwhile, first incineration plants were constructed with regard to human's health and environmental protection. During 1950s and 1960s filters were installed inside incinerators in order to mitigate air pollution. However, due to the compositional differentiation in the increased MSW components further technological improvement was required (Brunner and Rechberger 2015).

Improper management of MSW can cause air, water, soil, and aesthetic contamination at different scales. Open dumping of waste, which is a common practice in poor economies, results in water bodies' pollution and threatens public health, due to the release of organic and inorganic contaminants. Leaching of toxic pollutants affects surface and groundwater systems. Moreover, incineration of waste emits persistent organic pollutants, whereas landfills can generate methane (GHG) when organic materials decompose (Vergara and Tchobanoglous 2012; Das et al. 2019).

Environmental protection and public health were the main drivers to eliminate uncontrolled waste disposal. Technical standards started to gradually develop. Moreover, waste hierarchy emerged as an important driver in Europe in 1977, where more sustainable options such as reduction, reuse, recycling, and energy recovery from waste were introduced (Wilson 2007). Environmental Protection Agency of US (EPA) established the Resource Conservation and Recovery Act (RCRA) regulations for non-hazardous and hazardous waste as well as for used oil management and standards or underground storage tanks (Bajpai and Tyagi 2006). The RCRA law covers both hazardous and solid waste. With RCRA, US EPA was able to address hazardous waste throughout the entire life cycle of wastes (known as "cradle-to-grave"). Moreover, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), also known as Superfund, was enacted by US Congress in 1980. This specific act created a tax for petroleum and industrial industries and provided federal authority for facing releases of hazardous substances to the environment. In 1986, CERCLA act was amended by the Superfund Amendments and Reauthorization Act (SARA). Innovative technologies for cleaning up of hazardous waste sites and revision of the Hazard Ranking System (HRS) were regulated (Vallero 2019).

During 2015, the introduced "environmental" tax obligated manufactures and importers of recyclable goods to pay non-tax revenues of the federal budget. Regulation of MSW treatment activities was introduced in 2016 inside Federal Law No. 89 as an independent chapter, where regional operators have been nominated for several activities such as accumulation, transportation, treatment, and disposal (Kortov et al. 2016).

In Korea, waste management legislation was enacted in 1960. By the establishment of the Waste Management Law in the middle of 1980s, waste management involved not only waste minimization, but also suitable treatment methods and maximization of materials recycling (Yang et al. 2014).

According to EU policy on waste management (Directive 2008/98/EC of the European Parliament, Article 4), the following waste hierarchy should be applied

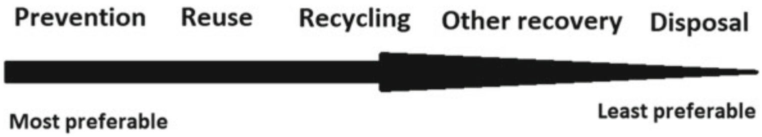

Fig. 10.2 Waste management hierarchy

(Gopinath et al. 2010): (1) prevention; (2) preparing for reuse; (3) recycling; and (4) other recovery, including energy recovery and (5) disposal (Fig. 10.2).

Member States shall take all the appropriate measures for waste hierarchy application in order to deliver the best environmental outcome. Moreover, general environmental protection principles such as precaution, sustainability, technical, and economic feasibility as well as humans' health and socioeconomic impacts have to be taken into consideration. Even if prevention is the first priority in the Waste Frame Directive (WFD), different waste management operations are essential to regulate landfill and incineration (Aziz and Maulood 2015; Thapa et al. 1970).

10.3 Energy Supply and Demand

Global human's population is expected to reach 9.6 billion by 2050. Energy demand will be definitely increased and WtE markets are going to be expanded by 2023. Potential energy of 13 GW could be generated globally from WtE facilities (Mubeen and Buekens 2019).

According to International Energy Agency (IEA), global oil demand is projected to reach 101.6 mb/d in 2023. In order to meet the expected growing demand, producers from Middle East will dominate in global oil supply market. However, demand is going to peak earlier compared to pre-pandemic forecast if governments adopt stronger policies and shift on renewable energy (Calhoun 1963).

Currently, bioenergy accounts for one-tenth of the global primary energy supply. Biofuel consumption increased 5% between 2010 and 2019. IEA's Net Zero Scenario estimates that biofuels derived from waste and non-edible energy crops could contribute around 45% to biofuel consumption instead of 7% in 2020. Nevertheless, advanced technologies for these types of feedstocks will need to be commercialized (Neamah 2014).

Global biofuel demand is projected to be increased by 28% by 2021–2026. The main driver for biofuel demand is government policies; however, other parameters such as total transport fuel demand, costs, and appropriate policy design could affect demand's fulfilling (IEA 2021).

Mitigation of climate change and GHG emissions are ongoing concerns that have shifted governments to regulate new policies during last two decades. Toward this direction, bioenergy supply chain has to be designed efficiently. Stricter regulations can potentially increase the share of renewables in total energy consumption (Daneshmandi et al. 2022).

10.4 Sustainable Waste Management

Waste is considered as the result of inadequate contemplation. Waste classification is a difficult task, because the composition of waste is different around the globe; whereas most countries have established their own classification systems (Wen et al. 2013).

Waste management is "set of interacting units or elements that form an integrated whole intended to perform some function" (Clark 1978). Conventional approach for waste management encountered waste generation, collection, and disposal methods as independent processes. Nevertheless, these procedures are definitely interlinked. Hence, in order to shift to a sustainable waste management, several parameters regarding system's efficiency have to be taken under serious consideration (Seadon 2010).

Sustainability is an internationally leading topic that is continuously analyzed by researchers, policymakers, and society members. Conservation of resources with regard to environmental protection and human health is the main priority of sustainable waste management (Fig. 10.3) (Gören 2014).

Key challenges for sustainable waste-to-energy improvement in developing countries that have to be addressed include: establishment of regulations and technical standards, business model design, technical localization, labor training, and fly ash treatment (Yan and 2020).

"***Zero waste***" concept is a visionary waste management system to deal with waste issues in the twenty-first century. Proper waste management policies, plans, and initiatives are of great significance in local and international levels. Zero landfilling and maximum resource recovery from waste are the main goals of "*zero waste*" approach. Identification of priority of waste strategy fields and development of national "*zero waste*" guidelines can contribute to "*zero waste*" concept application widely (Zaman 2015). Nevertheless, "*zero waste*" achievement in urban centers remains utopian, unless a good understanding of inputs and outputs is well established. Reducing waste could be possible if there was expansion in the life of products;

Fig. 10.3 Sustainable waste management priorities

however, financial solutions are required. Circular systems need a cooperative effort from all stakeholders and policy support is essential (Awasthi et al. 2021).

Several models for waste management have been developed over the years. During the 1980s, earlier models covered MSW management focused on the relationship between each factor. Main intention was to minimize the cost of mixed waste management and to a lesser extent the recycling. Nevertheless, the term sustainable waste management was not used. On the contrary, during the 1990s, recycling and other waste management methods were included in most models. Sustainability was inserted as term and the main categories of models were cost–benefit analysis models, life-cycle inventory models, and multi-criteria models (Morrissey and Browne 2004).

Solid waste management (SWM) has the potential to be more effective by the establishment of environmental strategies based on “reduce”, “reuse”, and “recycle” (3R) concepts. Sophisticated techniques should be applied in global level, where developed nations can share the knowledge and new methodologies, setting the good paradigm for developing countries. Of course, economic feasibility is essential to be evaluated in the long run and life-cycle assessment (LCA) models should be improved (Das et al. 2019).

Integrated approach for solid waste management includes the combination of several methods for both developed and developing countries. Different collection and treatment options as well as stakeholders’ involvement and development of relevant technologies related to products’ design are crucial (Joseph 2006).

Toward a circular economy, waste reduction and material reusability are of great significance. Waste materials from tires, glass, and plastic are generated in large volumes in many countries and undergo mainly landfilling. New strategies and economical solutions are vital to extend products’ life and to improve utilization of recycled materials (Ferdous et al. 2021). Moreover, direct and indirect emissions can be reduced by utilization of waste recycling and recovery. Bio-waste, plastics recycling, and energy recovery are key sustainability factors for waste management systems to protect human health and to minimize environmental impact (Maria et al. 2020).

10.4.1 Waste-to-Energy Conversion Technologies

WtE comprises a rapidly growing and eco-friendly approach to waste treatment. The term WtE is used interchangeably and involves a variety of processes for several streams conversion to energy. Promising conversion technologies include thermal conversion methods (incineration, pyrolysis, and gasification), biochemical methods (anaerobic digestion and alcohol fermentation), and landfill gas recovery (Beyene et al. 2018; Foster 2021).

In general, waste can be classified as urban, industrial, biomass, and biomedical waste. Utilization of WtE strategies can achieve sustainable waste management.

Potential renewable resources include agricultural, industrial, and municipal solid waste (Rajesh and Majid 2019).

MSW has either solid or semisolid form and is generated in municipal areas. Basically, MSW presents heterogeneous nature and its composition varies throughout the world. Major components are organic matter, paper, metal, glass, plastic, textile, wood, etc. Currently, major technologies for MSW management are incineration, composting, and landfill (Rao et al. 2017).

Improvement of WtE technologies for MSW management can reduce GHG emissions especially in developed countries, where WtE facilities are more applicable. In the US, there are 86 WtE facilities, mainly in New York and Florida. WtE facilities include mass burn and refuse-derived fuel technologies. However, presently only 13% of MSW is utilized for energy recovery, whereas 53% is landfilled. Landfilling and anaerobic digestion with gas recovery are the most widely used WtE methods for MSW management. Future technologies include plasma with fluidized bed gasification, plasma-assisted gasification, gasification with pyrolysis, etc. (Chand Malav 2020). In Europe, energy recovery from MSW is mainly applied in Germany, France, and UK. Nevertheless, incineration capacity of 18 countries is less than a quarter compared to MSW generation, whereas in 10 countries incineration capacities do not exist at all. In 2016, there were 512 WtE plants in Europe, while 330 new plants present the potential to be built for energy recovery from waste with a total capacity of about 50 million tons (Scarlat et al. 2018a). Generally, advanced waste management technologies aim to reduce the final disposal of waste. Incineration is mostly applied and if this option is not possible, waste is landfilled (Mubeen and Buekens 2019). Future trends in WtE technologies include biological hydrogen production, dark fermentation, and bioelectrochemical processes, such as microbial fuel cells (MFC) and microbial electrolysis cells (MEC). MFC and MEC are considered the most eco-friendly for conversion of MSW to energy (Beyene et al. 2018). In Fig. 10.4, current and future trends in WtE technologies are illustrated.

In developing countries, WtE plants have been constructed in some cases; however, the development of WtE technologies requires financial support and government regulations. Main challenges include sorting and handling of enormous volumes of MSW, economic instability, and lack of sustainable MSW management strategies (Kumar and Samadder 2017; Khan et al. 2022).

Biomass waste-to-energy technologies can also be applied for biofuel production. Liquid biofuel is an important alternative to fossil fuel in both air and ground transportation. The aviation sector is a fast-developing transport sector and its contribution to GHG emission reduction is very significant. Development of SAF can be achieved based on materials and production methods used in ground transportation. SAF properties must meet specific standards regarding engine operating conditions, storage, environmental, and safety concerns (Gil 2022; Yilmaz and Atmanli 2017). Production of SAF from biomass sources is an integration of several technologies such as thermochemical and biochemical conversions. Second-generation (2G) biomass sources, which include non-edible crops, lignocellulosic materials, and organic waste (such as MSW), are rich in fatty acid components and can undergo both thermochemical and biochemical conversion methods (Wang et al. 2019; Anjani et al. 2021).

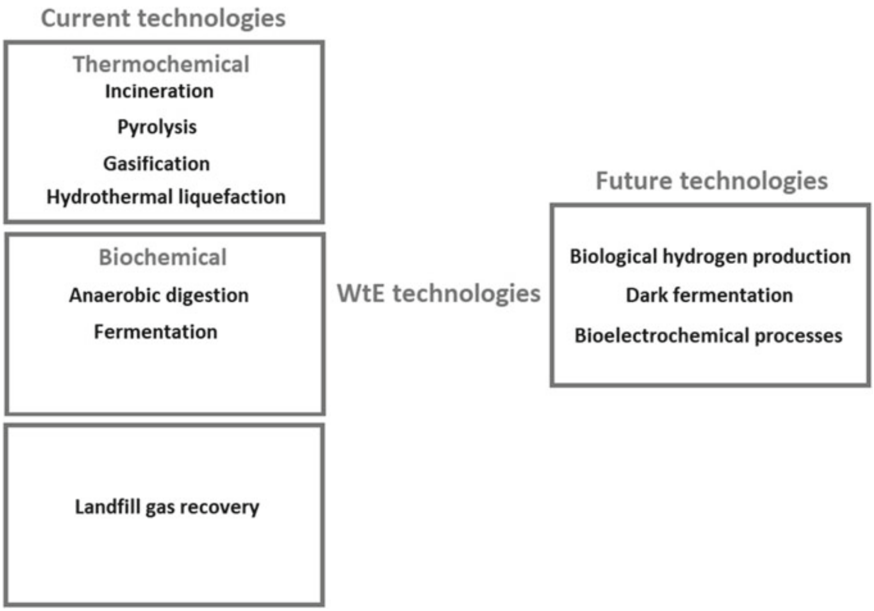

Fig. 10.4 Current and future WtE technologies

10.4.1.1 Thermochemical Conversion Technologies

Incineration is a thermal process that is applied for degradation and deconstruction of organic matter in a furnace by monitoring burning at high temperatures between 750 and 1100 °C in the presence of oxygen. It is considered as one of the most effective and mature methods, as it decreases the volume of solid waste up to 90%. Main stages of incineration process are drying and degassing, pyrolysis and gasification and oxidation. However, additional treatment of flue gas system is required (Makarichi et al. 2018; Beyene et al. 2018; Saini and Saini 2021), due to the release of gaseous pollutants and heavy metals. Hence, careful waste sorting is essential as some materials are non-combustible or hazardous and should not be incinerated. Pretreatment methods are also needed in order to reduce the moisture content in cases such as food waste (Jeevahan et al. 2018).

Pyrolysis is a thermochemical process where waste materials are combusted in the absence of oxygen at high temperatures of 500–800 °C. Char, oil, and gas are the main products. This method is the best in case of MSW management; however, it presents high operational and maintenance costs when applied at commercial level. Common types of pyrolysis are: conventional, fast, and flash pyrolysis. Waste separation is not required and environmental issues are limited. The gas produced during pyrolysis is called syngas and consists mainly of methane, hydrogen, carbon monoxide, and carbon dioxide. Syngas can be utilized in several energy applications such as engines, boilers, and biofuels production (Mubeen and Buekens 2019; Beyene et al. 2018; Saini and Saini 2021).

Gasification is also a thermochemical method that involves the conversion of organic matter into syngas in a controlled oxidizing environment at high temperatures of 800–1200 °C) without combustion. The volume and the mass of waste can be reduced by 90% and 70%, respectively. Solid and semisolid waste are utilized in this method, where in case of MSW gasification is a well-established process for renewable energy production (Mubeen and Buekens 2019; Foster 2021; Moya et al. 2017).

Hydrothermal liquefaction (HTL) is a thermochemical process for both dry and wet biomass conversion into crude bio-oil at high pressures (50–250 bar) and temperatures (250–400 °C) that is further upgraded and refined into liquid biofuels. Wet biomass is used without any drying requirement. However, due to higher water and oxygen content of bio-oil more research is needed for its utilization as drop-in fuel (Foster 2021; Perkins 2019).

10.4.1.2 Biochemical Conversion Technologies

Anaerobic digestion (AD) is a biological process that is used for the decomposition of organic matter from bacteria in the absence of oxygen. Biogas is produced and consists mainly of methane and carbon dioxide. Feedstocks include MSW, biosolids, manure, etc. Power, heat, and biofuels can be obtained from biogas; however, compared to other WtE technologies, AD is still considered as not economical (Kumar and Ankaram 2019; Mubeen and Buekens 2019; Beyene et al. 2018).

Fermentation is a biochemical reaction that involves the conversion of organic materials into an alcohol and an acid in the absence of oxygen. Bio-ethanol has been produced in large quantities from food waste after pretreatment due to the complex nature of lignocellulosic components. Any material that contains sugar can be converted into ethanol. Three main types of feedstocks are sugar-, starch-, and cellulose-based materials. Starch should be firstly hydrolyzed by enzymes in order to generate fermentable sugars, whereas in case of cellulose depolymerization of carbohydrates is also required (Mubeen and Buekens 2019; Beyene et al. 2018; Jeevahan et al. 2018).

10.4.2 Landfill Gas Recovery

Sanitary landfilling is a WtE technology that involves the controlled disposal of waste on land in order to eliminate environmental contamination through biogas recovery and leachate management. A promising approach for energy recovery is the construction of biogas production plants from landfill gas recovery. In US, there were 654 biogas recovery plants from landfills in 2017, where the energy potential of biogas reached 8.0 billion m^3 of biogas/year. In Europe, landfill biogas is mainly produced in Italy, UK, France, and Spain. Also, it dominates the market in Portugal, Greece, Estonia, and Ireland (Scarlat et al. 2018b).

Nevertheless, environmental impact is higher compared to other disposal methods, since, especially in most developing countries, unsanitary landfilling is applied as a simpler practice. Hence, restrictions for MSW disposal on landfill sites motivated governments to adopt more efficient methods for disposal (Kumar and Samadder 2017). Although waste landfilling is currently considered as a generally accepted low-cost method, regular monitoring is required. EU Directive aims to reduce the waste in landfills, even if in many European countries, landfilling is still the main waste management technology (Vaverková 2019).

10.5 Waste Materials as Biojet Fuel Feedstock

10.5.1 Decarbonizing Aviation Industry

Aviation sector is one of the most rapidly growing transportation sectors and plays a key role in global economy. Sector's emissions contribute around 2% of total carbon dioxide (CO_2) emissions globally. COVID-19 pandemic has certainly affected sector's emissions. However, pre-COVID levels are projected to be reached soon. Hence, decarbonization of aviation industry is an ongoing challenge and contribution of SAF is of great significance to achieve early and deeper CO_2 reduction emissions by 2030 and 2050, respectively (Abrantes 2050; Gollakota and Shu 2022).

The aviation industry has set ambitious targets to reduce its environmental impact while contributing to economic growth. In 2009, the International Air Transport Association (IATA) aimed to stabilize CO_2 emissions after 2020 by implementing a combination of factors including fleet renewal, infrastructure measures, use of renewable fuels, etc. Compared to other solutions that has been proposed, biojet fuel utilization is currently the most attractive option to operate in the existing aircraft engines as blends with conventional jet fuels (Kousoulidou and Lonza 2016).

Europe's Biofuel Flight Path Initiative was introduced in 2011 by European Commission in partnership with airline and biofuel producers to support the use of biojet fuels (Deane and Pye 2018). Aviation emissions were inserted in EU emission trading scheme since 2012, while in 2016 the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) was introduced in the International Civil Aviation Organization (ICAO) (Gray et al. 2021).

The International Energy Agency (IEA) stated that in order to achieve a 2 °C target, aviation emissions should not exceed 1000 Gt of CO_2 from 2011 onward (Stupp et al. 2012). In 2019, aviation sector was responsible for million tons (Mt) of CO_2 emissions. Top emitter of GHG emissions was USA. GHG emissions came from aviation bunkers and amounted to 179 Mt of CO_2. Together with USA, other counties such as China, UK, Japan, and Germany contributed to 40% of global GHG emission from aviation bunkers. Since aviation sector's emissions are expected to increase in the future, negative-carbon technologies have to be developed along with bioenergy production (Hasan et al. 2021). In Europe, the Renewable Energy Directive (RED) motivated EU members to improve the production of biofuels from several biomass sources. Nevertheless, utilization of food crops for biofuels production remains an ongoing concern regarding GHG emissions due to the indirect land use (Aracil et al. 2017).

In order to achieve a sustainable energy system and meet long-term GHG emissions target, EU has adopted ambitious energy and climate regulations in its 2030 framework. Research and development of innovative eco-friendly technologies could contribute to sector's emissions reduction, according to the Aviation Strategy for Europe. EU target policy for 2020 does not specify the exact targets for transport sector, but emphasizes on low-carbon technologies application (O'Connell et al. 2019).

Biojet fuel market is entirely connected with stringent requirements of GHG emission standards that are stated by ICAO and aviation industries ought to pay credits in case of not satisfying the regulations. Due to high safety requirements, only drop-in SAF with excellent performance in jet engines can be used according to approved American Society for Testing Material (ASTM) D7566 standard (Reaching 2021; Zhang et al. 2020).

10.5.2 Waste Material Feedstock

Biofuels, including SAF, can be produced by a plethora of feedstocks such as MSW, agricultural and crop residues, energy crops, sewage sludge, livestock manure, and other organic materials. Biomass is a renewable organic material that can be converted into biofuels and chemicals. First-generation biomass mainly includes edible plant materials, whereas second-generation biomass consists of non-edible plant residues and third-generation biomass of micro- and macro-algae (Nanda et al. 2018).

In general, second-generation biofuels are more suitable for biofuels production as they do not compromise food security and direct land use. Non-edible feedstock, lignocellulosic biomass, waste cooking oils, and organic have overcome the limitations of first-generation feedstock and can be converted into biofuels by both thermochemical and biochemical methods. Moreover, agricultural wastes are still underutilized and can be potentially used as an alternative feedstock for biofuels and value-added chemicals production in near future (Anjani et al. 2021; Osman et al. 2021). Waste biomass feedstocks (Fig. 10.5) that can be utilized for SAF production are further reported.

MSW provides an alternative feedstock for SAF production in agreement with circular economy concept. According to European waste hierarchy, only the non-recycled fraction of MSW can be used for energy recovery, including biofuel production (Aracil et al. 2017).

Food waste consists mainly of highly degradable compounds such as lipids, protein, and carbohydrates. It is generated from food processing plants, kitchen,

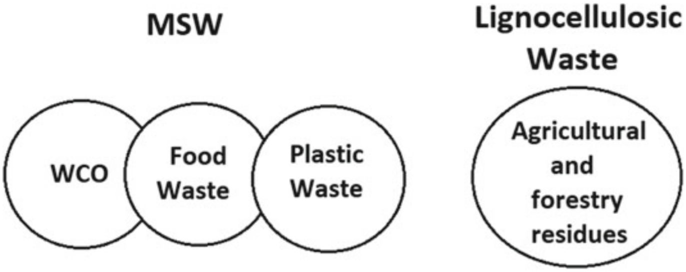

Fig. 10.5 Waste feedstocks for SAF production

restaurants, industries, agricultural field, etc. and accounts around one-third of MSW. Biofuels such as bio-oils, syngas, and bioethanol can be produced as main products through pyrolysis or biochemical conversion (Yukesh Kannah, et al. 2020; Sridhar 2021).

Waste triglyceride feedstock includes waste cooking oil (WCO), animal fat, oil extracted from industrial residues, and bio-oil from pyrolysis. WCO is oil residue that is produced after cooking. It is considered as a serious environmental hazard if disposed improperly. It is mainly generated from households, restaurants, and food industries and contains triglycerides and high amounts of free fatty acids (FFAs) and water. Utilization of WCO as an alternative feedstock for biofuels including SAF could be really promising for future energy needs (Foo et al. 2021; Goh 2020).

Lignocellulosic feedstock includes mainly agricultural and forestry residues as well as textile and solid urban waste. Due to the abundance of this renewable type of feedstock, lignocellulosic waste materials are an attractive option for SAF production. Their contribution in total SAF production will be really beneficial (Moreno-Gómez et al. 2020). Nevertheless, due to highly recalcitrant nature of lignocellulosic biomass, deconstruction of lignocellulosic matrix into its components (cellulose, hemicellulose, and lignin) is required. Deconstruction can be achieved through several pretreatment methods including physical, chemical, biological, physico-chemical, or combination of them. The selection of the most appropriate pretreatment method depends on the downstream applications of lignocellulosic biomass (Ashokkumar et al. 2022; Costa et al. 2020).

Finally, plastic production in recent years raised the interest for their potential utilization as feedstocks for biofuel production. Due to their slow degradation and limited recycling rate after disposal, plastics can be used as potential feedstock for SAF production through thermal processes (Zhang et al. 2022; Fahim et al. 2021).

Waste feedstock is a renewable raw material for SAF production and due to its abundance, it can guarantee the supply of production process. Moreover, its utilization as feedstock minimizes waste disposal issues and the cost of waste materials is much lower than other feedstock. For oleochemical feedstock, WCOs have been mostly investigated for SAF production, whereas for lignocellulosic-based materials agricultural and forestry residues gained the attention (Moreno-Gómez et al. 2020). Neste has identified 30 million tons of waste feedstock that could be used for biojet fuel production. However, since there is a significant gap between biojet fuel price and convention jet fuel, effective policies are essential to encourage the production and use of biojet fuel in the short-to-medium term. Technology push and market pull policies can promote development and market penetration of biojet fuel (Reaching 2021).

10.6 Sustainable Pathways for Greener Biojet Fuel Production

To date, eight pathways for SAF production have received certification by ASTM to be used as blends with conventional jet fuels in order to meet the specific requirements in existing aircraft engines. In Table 10.1, ASTM-certified pathways and the year of receiving certification are presented, while further down detailed description of each production route is given (Reaching 2021; Wang and Tao 2016).

The most widely used route for SAF production is Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK) or catalytic hydroprocessing. This pathway is fully commercialized and involves biojet fuel production through hydroprocessing of vegetable oils, animal fats, waste grease, and algal oil (oleochemical feedstocks). ASTM certification was received in 2011 for maximum blend level of biojet fuel of 50% with conventional jet fuels. Hydroprocessing of lipid feedstocks includes hydrotreating and hydrocracking reactions. In first case, carbon double bonds undergo hydrogenation followed under mild conditions by several catalysts such as Pd, Pt, NiMo, and CoMo over γ-Al_2O_3 or activated carbon. The majority of aviation biofuels is currently produced by HEFA pathway from oleochemical feedstocks and this technology is going to dominate over the next years (Monteiro et al. 2022; Chong and Chemmangattuvalappil 2021).

Chen and Wang (2019) investigated WCO conversion through hydroprocessing over Pd/C catalyst. High concentrations of C15–C18 normal alkanes were produced. Moreover, Xu et al. (2019) used a two-step catalytic conversion and hydrogenation of waste triglycerides into aviation range hydrocarbons with a maximum yield of 60%.

Table 10.1 ASTM-certified pathways for SAF production

Pathway	Year of certification
FT	2011
HEFA	2011
SIP	2014
SPK/A	2015
ATJ	2016/2018
Co-processing	2018/2020
CHJ	2020
HC-HEFA	2020

Main components of produced biojet fuel were found compatible to conventional aviation fuels. Asiedu et al. (2021) investigated catalytic transfer hydrogenation of WCO over a fixed bed of granular activated carbon with a biojet fuel fraction yield of approximately 52%. In addition, Shah et al. (2019) studied catalytic pyrolysis hydrogenation over NiMo catalyst of agricultural wastes (eucalyptus sawdust) and waste frying oil. Obtained upgraded bio-oil exhibited similar properties with conventional aviation fuels.

Another promising technology based on gasification and further upgrading of biomass products is Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) pathway. Gasification combined with FT synthesis received certification under ASTM D7566 standard on 2009 and covers any type of feedstock allowing a maximum blend limit of 50% biojet fuel with conventional jet fuels. Syngas is produced by gasification of biomass feedstocks. It primarily consists of CO and H_2, which are the building blocks for FT liquid hydrocarbons synthesis (Wang and Tao 2016; Ng et al. 2021; Richter et al. 2018). The length of final products depends on catalyst, pressure, and temperature. Several catalysts have been reported such as Fe, Co, and Ru based on supported materials (Martínez del Monte et al. 2019; Liuzzi et al. 2021).

Several thermal processes can be applied to convert plastics into biofuels that have unlimited applications in airline industry, as well as in transportation and power generation industries (Fahim et al. 2021; Erdoğan 2020). Among them, catalytic pyrolysis is a promising conversion method. Improvement of bio-oil quality under the most economic viable way is an ongoing concern for researchers (Saha et al. 2019). Sarker et al. (2012) investigated the production of aviation range hydrocarbons from polystyrene (PS) waste plastics through thermal degradation and fractional distillation. Biofuel yield reached 23% having a carbon range of C_6–$C_{16.}$ Moreover, Ali et al. (2021) proposed pyrolysis of waste plastic feedstock over graphite as catalyst and an output of 80% of biojet fuel was observed having similar chemical properties with conventional aviation hydrocarbons. In addition, according to Liu (2020), catalytic hydrocracking of polyethylene (PE) over bifunctional catalyst Pt/Al/MCM-48 produced biojet fuel range hydrocarbons with a yield of 85.9%.

Synthesized paraffinic kerosene with aromatics (SPK/A) pathway has been certified by ASTM in 2015 allowing a blend limit of 50%. This is also a thermochemical production method based on FT synthesis and involves the addition of light aromatic compounds. Potential feedstocks for biojet fuels production include coal, natural gas, and biomass-based materials. However, it is still in demonstration stage based on fuel readiness level (FRL) (Reaching 2021; Abrantes 2050).

Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK) pathway involves dehydration and oligomerization of alcohols into biofuel hydrocarbons. Isobiobutanol AJT pathway is approved by ASTM in 2016 allowing 30% blend of biojet with jet fuels, whereas ethanol AJT pathway received ASTM approval in 2018 with a maximum blend limit of biojet fuel 50%. Feedstocks include sugars from starch-rich or from lignocellulosic biomass. An ongoing challenge of this pathway is the high market value of alcohols as intermediates, as well as feedstock sustainability and availability (Reaching 2021; Bauen et al. 2020; Susan van Dyk 2021).

Synthesized iso-paraffins from hydroprocessed fermented sugars (SIP-SPK) pathway or also known as direct sugars to hydrocarbon conversion (DSHC) was certified by ASTM in 2014. Sugar feedstocks are fermented into C15 hydrocarbon compounds which are further upgraded to biojet fuel hydrocarbons. Maximum blend limit is 10% of biojet fuel with conventional jet fuels. However, due to the low energy input, this type of fuel is more viable for value-added chemical production (Anjani et al. 2021; Susan van Dyk 2021).

More recent ASTM-certified pathways include: hydrocarbon-HEFA-synthesized paraffinic kerosene (HEFA/SPK) pathway, catalytic hydrothermolysis jet (CHJ-SPK) pathway, and co-processing technologies. HEFA/SPK route was certified by ASTM in 2020 and bio-derived lipid feedstock is derived from microalgal species, Botryococcus braunii. Maximum blend limit is 10% and currently this method is under pilot to demonstration at technological level (Reaching 2021; Goh 2022). Catalytic hydrothermolysis jet (CHJ-SPK) pathway received ASTM certification in 2020 for blending limits up to 50%. It involves conversion of lipid feedstocks to bio-crude oil and further upgrading through hydrothermal liquefaction technology. However, it is still in pilot stage of development (Reaching 2021; Susan van Dyk 2021). Finally, co-processing technologies involve lipid and FT liquid conversion through hydrotreating processes in existing petroleum refineries and in both cases a blending limit of 5% is allowed. Lipids as intermediates received ASTM 1655 certification in 2018, whereas FT liquids in 2020 (Susan van Dyk 2021; Van Dyk 2019).

Minimum jet fuel selling price (MJFSP) estimation results reveal that there is a wide range in prices between ASTM-certified production pathways, depending on feedstock type and production cost. In most of biojet fuels, MJFSP is higher compared to the selling price of conventional jet fuel (approximately 18 $/GJ). In fact, recent literature data indicate a wide range of 23–310 $/GJ for HEFA pathway, 4–215 $/GJ for ATJ pathway, 31–108 $/GJ for CHJ pathway, 34–82 $/GJ for FT pathway, and 37–60 $/GJ for SIP pathway (Dahal 2021). HEFA and ATJ pathways are more sensitive to feedstock cost, whereas gasification technologies present greater sensitivity to capital cost. The price gap between biojet and conventional jet fuels could be bridged by airlines as (a) for lower blends (5%) a small increase in ticket price could be paid by passengers, (b) passengers may have the opportunity to voluntarily pay a further fee, and (c) airports may offer initiatives for biojet fuel usage (Reaching 2021).

In terms of CO_2 emissions, SAF is responsible for the generation of less than 80% of CO_2 compared to their fossil-based counterparts. It is estimated that CO_2 will be reduced around 11% in 2050, by increasing SAF uptake (Hasan et al. 2021). Gasification and FT pathways for biojet fuel production present lower emissions than hydroprocessing or combined pyrolysis and hydroprocessing. In case of lignocellulosic feedstock, forestry residues perform the lowest GHG emissions (O’Connell et al. 2019).

10.7 Conclusions

Through suitable WtE technologies, waste materials such as MSW as well as agricultural and industrial residues can be converted into proper energy forms. Besides electricity and heat production from waste, biomass-based waste materials can be used as feedstocks for biofuel production, including biojet fuels.

Decarbonization of the transportation sector is an ongoing concern. Aviation industry contributes to approximately 2% of global GHG emissions. Since aviation sector will continue to grow over the following years, alternative kerosene drop-in fuels provide a promising solution to existing aircraft infrastructure. Sustainable aviation fuels can be produced from various waste feedstocks such as MSW, waste cooking oil, and lignocellulosic materials. Conversion methods include thermochemical and biochemical processes. Nevertheless, to meet ASTM standard requirements, biojet fuels can be used only as blends with conventional jet fuels up to a maximum blending limit of 50%.

Currently, eight pathways have been certified by ASTM for SAF production. HEFA pathway is the most mature technology and is fully commercialized. It involves catalytic hydrogenation of lipid feedstocks, including WCO. This conversion route is projected to dominate over the following years, although feedstock availability and cost remain challenging. Moreover, lignocellulosic feedstocks can potentially contribute to biojet fuel production in the medium to long term. Advanced thermochemical methods such as gasification-FT synthesis and HTL as well as biochemical ATJ process can be applied for a variety of waste feedstocks.

Waste-to-energy conversion methods can be utilized in biojet fuel production for a sustainable aviation industry. Proper solid waste management can contribute to efficient waste material recovery in order to meet the ongoing energy demand in aviation sector. Nevertheless, the commercialization of advanced biojet fuel production methods requires further research and development. The availability of raw materials, high production cost, and lack of policy support remain ongoing challenges for advanced methods.

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