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Waste to energy: Trends and perspectives

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ABSTRACT

Global waste generation is expected to continue to grow due to economic development and population growth. Therefore, sustainable waste management is mandatory if a sustainable world is desired in which the objectives of the circular economy concept are met, where recovery is the last step to be taken when reduce, reuse or recycle have already been carried out. Waste-to-energy processes could constitute a way to recover energy from waste, helping the access to renewable energy to the world population, in addition to a waste management system. The present review describes different wastes that can be employed in waste-to-energy processes, using thermo-chemical, biochemical and chemical processes. The energy produced can be in the form of heat, electricity or biofuels. For each of these processes, the feedstock used, the state-of-the-art in recent years and the expected trends for the coming years are briefly discussed.

1. Introduction

Global energy demand has increased rapidly in the last century along with the improvement of living standard, rising fossil fuels consumption and waste generation [1,2]. Waste management has been carried out for a long time from a hygienic point of view, avoiding health problems in society [3]. However, the development of world's population must be environmentally and economically sustainable, addressing climate change immediately [4]. Thus, energy supply and waste management are great current challenges that humanity has to face [2]. The growing inclusion of renewable energies in the energy mix together with a proper treatment and management of waste will be help to a global sustainable development.

Regarding waste generation, one third of the world's waste comes from the high-income countries, which represents the 16% of global population [5]. The global waste production reached the 2.01 billion tons in 2016 and the projections by 2050 imply a waste increase of almost 70% more than in 2016 [6]. Circular economy concept could minimize the waste generation applying the four r's: reduce, reuse, recycle and recover. Recover refers to the last step that should be taken when the previous ones have been undertaken [7]. The recovery of waste as an energy vector or a by-product could contribute to the reduction of waste disposal problems in the future. Besides, the waste-to-energy (WTE) concept could ensure access to energy to all world's population [8]. However, current limitations related to waste collection, required waste pre-treatment and yield conversion of WTE could minimize cost-effectiveness of the conversion processes. Scientific advances will be able to solve these problems, promoting economically viable WTE routes and therefore an economy based on renewable energies [9].

The potential feedstock for WTE systems can be classified according to its origin: agricultural, industrial and residential [9]. Agricultural sector generates organic vegetable and animal wastes. Industrial sector can produce organic (e.g., by-products from sugar refinery, diary wastes, slaughterhouse animal waste or wastewater) and non-organic wastes (e.g., by-products from pulp and paper industry). The residential wastes are mainly produced in the kitchen, toilets or garden. The kitchen wastes involve municipal solid waste and used cooking oil. The treatment of toilets waste generates sewage sludge that can be recovered. The garden wastes comprehend vegetable wastes.

Agricultural, forestry or livestock waste, as well as industrial and residential waste, can be converted into energy through thermo-chemical conversion processes. Organic wastes from the agricultural and forestry sectors, such as lignocellulosic waste or forest cleaning waste, or wastes from the livestock sector, such as livestock slurry, are wastes suitable for obtaining energy through thermo-chemical processes. Additionally, non-organic wastes can also be employed. For the same purpose, some industrial waste can also be used, whether organic,

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such as waste from the food industry such as olive stone, or non-organic, such as waste from the paper industry. In addition, thermo-chemical processes can also be safely used for residential waste, such as municipal solid waste or sewage sludge. The most widely used thermochemical process is combustion. However, in recent years, gasification and pyrolysis have emerged at industrial level as more environmentally friendly thermochemical processes [10]. Currently 80% of the world's energy is produced via combustion or gasification [2].

Organic wastes from agricultural sector (e.g., lignocellulose, livestock manure), industrial wastewater and residential wastes (e.g., waste food, domestic solid waste, sewage sludge) can also be processed biochemically through microorganisms to produce energy as gas or liquid fuel to generate electricity [7]. The most available biochemical processes are anaerobic digestion and fermentation. Both processes may require pre-treatments and perform co-digestion or co-fermentation of different substrates to improve the biodegradability of the waste [11,12]. Although anaerobic digestion is a more widespread process than fermentation, the economic and sustainable feasibility of both biochemical conversion technologies should be assessed in detail.

Waste oils are the most suitable raw materials for processing to obtain biofuel as energy product, being compared with other feedstocks such as edible and non-edible vegetable oils [13,14]. Besides, the conversion of waste oil-based materials into energy products can mitigate disposal, water contamination and drainage systems blockages issues [15]. The waste oils can be collected from restaurants (47%), food industries (32%) and households (18%) [16]. The economic feasibility of chemical conversion of waste oils is mainly influenced by the cost of (i) waste collection/transport and (ii) biofuel production process [17]. The transport cost can range between 15.1% [18] and almost 23% [17] of the overall cost of biofuel production from waste oils. The minimization of logistics costs can be achieved (i) optimizing transport routes with commercial vehicles [18] or (ii) performing required pre-treatment of waste oils close to their collection point when the biofuel production facility is far away [17]. Regarding the chemical conversion of waste oils, transesterification is the most widespread process to obtain biodiesel as biofuel [19]. The low-cost and high-availability of oil-based waste resources allow the biodiesel production cost to be reduced by up to 70% compared to current processes [13,20]. Nowadays, the 76% of oils used to produce biodiesel comes from edible and non-edible vegetable oils [16] assuming up to 80% of the total cost of biodiesel production [21,22]. The minimization of transesterification process cost makes waste oils a good candidate source of biodiesel production in the short term. Besides the transesterification process, another promising chemical conversion based on the hydrogenation of oils (HVO) has emerged in the last decade. Oil-based waste sources can be hydrotreated, producing a renewable diesel fuel which could be a direct substitute for fossil diesel in current engines [23]. Biofuel from the HVO process ranks third behind ethanol and biodiesel [24], given its advantageous technical characteristics (i.e. high cetane number; high oxidation stability; non-presence of sulphur, oxygen and aromatic hydrocarbons; low NO_x emissions; among others) [23]. Moreover, the HVO process can be carried out in existing infrastructures of fossil fuel refineries, and may become more economically feasible compared to biodiesel production from transesterification [25].

Several forms of energy can be obtained depending on the waste used as feedstock and the WTE process employed. The wide variety of waste feedstock is reflected in Table 1 where they are gathered, briefly characterized and the technologies which might be used to obtain a final energy product presented. While some thermo-chemical processes provide thermal energy, electrical energy and biofuels; other biochemical or chemical processes are focused on obtaining biofuels.

In general terms, wastes with high moisture content are converted into biogas through anaerobic digestion (i.e. industrial wastewater, livestock manure, sewage sludge). Solid waste is mainly processed to produce thermal energy or intermediate products, such as syngas or hydrogen (i.e. municipal solid waste, lignocellulosic waste). However, the biogas production from anaerobic digestion of solid organic wastes may also be considered as a potential energy conversion way. Oil-rich wastes are mostly converted through transesterification or hydrogenation processes into biofuels such as renewable diesel or biodiesel (i.e. microalgae, waste oil). Lignocellulosic wastes and sugar or starch containing wastes may also be processed through alcoholic fermentations to mainly produce bioethanol or biobutanol. A waste source can be valued through different technologies to obtain specific energy products. Moreover, the full integration of waste conversion technologies into biorefineries strongly improves the energy use of waste (i.e. anaerobic digestion could be coupled to thermochemical conversion technology to promote circular economy and to improve the feasibility of the waste conversion process [54]).

Table 1
Waste feedstock, technologies and final energy products.

Waste feedstock	Technology	Final energy product	Ref.
Lignocellulosic Waste Biomass: • agricultural crop residues: ○ field residues. ○ agro-food processing residues. • forestry biomass wastes.	Pyrolysis Gasification Combustion Fermentation	Syngas, bio-oil, biochar Syngas, biochar Thermal energy Bioalcohols, Hydrogen	[26] [27] [28] [29]
Agricultural wastes from: • corn stover • sugarcane residues	Anaerobic digestion Alcoholic fermentation	Biogas, biomethane Biofuels	[30] [31]
Municipal solid waste (MSW):	Anaerobic digestion (water content > 70%) Pyrolysis Gasification Combustion	Biogas, biomethane Syngas, bio-oil, biochar Syngas, biochar Thermal energy	[32–34] [35] [36–39] [38,40]
Livestock manure & corps	Anaerobic digestion	Biogas, biomethane	[41]
Sewage sludge • wastewater treatment plants	Anaerobic digestion Pyrolysis Gasification Combustion	Biogas, biomethane Syngas, bio-oil, biochar Syngas, biochar Thermal energy	[42,43] [44] [10] [45]
Waste food	Anaerobic digestion	Biogas, biomethane	[33,34]
Industrial wastewater • COD of 3000–40,000 mg/L • COD 1500–3000 mg/L	Anaerobic digestors	Biogas, biomethane	[46]
Microorganisms: • photosynthetic eukaryotic • prokaryotes microalgae	Anaerobic digestion Alcoholic fermentation	Biogas, biomethane Bioethanol	[47,48]
Waste oils	Transesterification Hydrogenation of oils	Biodiesel Renewable diesel	[49–51] [23,52,53]

The potential research and development activities that could improve the economic feasibility of WTE facilities in the next years are summarized in the following paragraphs. Improving WTE conversion in existing facilities and developing technologies for next generation facilities is important to localities across the world as they explore more cost-effective solutions to waste disposal.

2. Thermo-chemical conversion

Thermo-chemical processes can transform different types of agricultural, industrial or residential waste into energy. Suitable wastes to produce energy by thermo-chemical process could be: agricultural waste from the livestock sector, such as livestock slurry, or vegetable waste from the agricultural and forestry sectors, such as lignocellulosic waste or forest cleaning waste; industrial waste from the food industry, such as olive stone or almond shells, and from other industries such as paper industry or plastic industry; residential waste, such as municipal solid waste or sewage sludge.

There is a wide variety of thermochemical processes, some better known and used on an industrial scale, such as combustion, gasification or pyrolysis, and others less well known, such as torrefaction, hydrothermal processes, cracking and hydrocracking. According to the thermochemical process used, the renewable energy obtained can be in the form of heat, electricity, syngas, bio-char or bio-solid and bio-liquids or advanced biofuels.

Although all WTE processes achieve a reduction in waste volume, some thermochemical processes achieve a greater reduction, as the solid fraction is reduced to ash. In addition, these processes have other advantages over other WTE processes. On the one hand, thermochemical treatments allow the sanitisation of the waste by subjecting it to high temperatures, which leads to the destruction of viruses, bacteria and prions. In addition, thermochemical processes can mineralise and immobilise organic substances. The products resulting from thermochemical processes can be considered as a higher value-added resource, however, they need to be treated in order not to be considered as hazardous waste. Thus, the emission control of these installations must be exhaustive and costly, but the appropriate technology is now available [3].

The trends and perspectives the WTE thermochemical processes of combustion, gasification, pyrolysis, torrefaction, hydrothermal processes and cracking processes are described below.

2.1. Combustion

Combustion processes allow the transformation of the chemical energy contained in the waste into thermal energy, by using an excess of air, at temperatures between 850 °C and 1200 °C. Incineration is the same as combustion, naming incineration when the main objective is the destruction of something via burning, as is the case for some waste [55]. It is the most mature and widely used technique [56]. However, useful work that can be extracted from heat energy has a yield due to the limitation of the Carnot cycle [2].

In order to be used as a fuel in a combustion process, a waste has to have the property of releasing thermal energy when it is violently oxidised. Many wastes can be used in a WTE process through combustion, some examples could be agricultural or forestry waste, paper waste, municipal solid waste or sewage sludge. Depending on the type of waste, it is sometimes necessary to subject the waste to a pre-treatment process prior to the combustion process to adjust its moisture content, particle size or density. In addition, their chemical composition influences the quality of their emissions.

In recent years, research has been carried out on the combustion of different wastes, mainly in solid form, such as sewage sludge [38,46], even in co-combustion with others fuels [45,57]; in liquid form, such as glycerol [58]; and gas form, as syngas from a gasification process [59]. Focus has also been made on different combustion technologies [60] that is dependent on the type of waste. Although the pre-treatment systems mentioned above allow the adjustment of some physical properties of the fuel, such as moisture, particle size or density, there are different technologies depending on the type of waste, the scale or the final energy use. For solid waste, at the industrial level, there are fixed bed combustion technologies, such as grate furnaces; fluidised bed combustion, which can be bubbling, circulating or pressurised, or pulverised fuel reactors when the particles are very fine. At the domestic level, solid waste can also be used in stoves or boilers that can be specifically designed for such waste, as is the case of the fixed bed boiler for the use of olive pits or almond shells. For liquid waste, at industrial level, there are boilers with injectors that allow the combustion of liquid fuels. For gaseous waste, at industrial level, there are gas boilers, such as cyclone or torsional boilers, which allow the combustion of syngas from gasification or pyrolysis. In addition, the combustion technology is related to the end use of the gas, as its thermal energy can be used for the production of steam that can be transformed into heat, cold or electricity or more than one in the case of cogeneration or trigeneration plants.

In recent years, the use of catalysts has also been studied to solve problems related to agglomeration or slagging [38], to increase process efficiency [61–63], and to reduce emissions, including carbon dioxide [57].

Emissions depend on the physico-chemical characteristics of the waste, the combustion technology used and the operating conditions. However, in order to comply with emission regulations, some emission reduction technologies may be necessary. Some are already used at industrial level, but are still being studied. Particulate matter can be abated with the use of mechanical separators: sedimentation chambers, cyclones, multi-cyclones and bag filters; scrubbers or electrostatic precipitators. To reduce NO_X, catalytic and non-catalytic selective reduction methods are used. To reduce SO_2 and HCl, scrubbing methods or particle injection methods are used. Recent studies has been performed to develop this area [64–66].In the near future, work will continue on improving combustion technologies to increase efficiency and reduce emissions. This will make combustion a more environmentally friendly process and will comply with increasingly demanding legislation. Furthermore, progress in carbon capture processes will enable the real decarbonisation of the planet.

2.2. Gasification

The energy contained in a waste can be converted into chemical energy contained in the synthesis gas through gasification, constituting a WTE process. Gasification process is a thermochemical process that is performed using less air than the stoichiometric for the combustion processes, and using high temperatures, between 800 and 1200 °C, depending on the feedstock and the technology. Synthesis gas is the main product of a gasification process. It contents carbon monoxide and hydrogen among other compounds, and it has multitude of applications for energy production, in the form of heat, electricity or biofuels, and even hydrogen [1], besides to its applications in the chemical industry. Additionally, biochar is obtained in the gasification process. It is a carbonaceous solid product with high energy content. Gasification can be one of the technologies used in a bio-refinery to obtain different forms of energy or products from waste.

A wide variety of wastes can be used as fuels in a gasification process, some examples could be the researcher studies on woody biomass [67] and municipal solid waste [36,37], the demonstration plant of sewage sludge and the industrial plants of meat and bone meal and waste from the olive oil industry. In some cases, pre-treatment may be necessary to reduce the moisture content and adjust the particle size.

There are several technologies that can be used in a gasification process: fixed bed (downdraft, updraft or crossdraft), fluidised bed (bubbling or circulating), entrained bed or plasma [37,68–71]. The quality of the fuel used, the gasification technology employed and the operating conditions are factors that determine the quality of the syngas generated. Hence, in the last few years, the gasification of different types of waste has been studied, as well as the development or optimisation of technologies for both gasification [67,69,72] and treatment of the synthesis gas produced [27,73]. These studies focus on upgrading the quality of the synthesis gas by reducing tars and other undesirable compounds and adjusting its chemical composition suitable for the end use [27,73], thus it can be used not only for the production of thermal or electrical energy, using combustion chambers, engines or turbines, but also for the production of biofuels such as green hydrogen, synthetic natural gas, methane or advanced biofuels such as Fischer-Tropsch diesel.

The trend for the future is to improve process efficiency and focus on energy production in the form of advanced biofuels with the aim of replacing conventional fuels in the current vehicle fleet, and above all on the production of hydrogen, the development of which will allow a real reduction in CO_2 emissions into the atmosphere due to transport.

2.3. Pyrolysis

Pyrolysis is a process that transforms waste, in the complete absence of air, into three products: liquid, gas and solid. Considering the WTE transformation, the most interesting is the liquid fraction, which is made up of oily compounds that can be used to produce liquid biofuels that can replace conventional fuels such as diesel or petrol. Additionally, the gaseous fraction is synthesis gas that can also be used to obtain energy, as in gasification. The solid fraction consists of char, which is usually used in agriculture or adsorption processes. Pyrolysis can be other of the technologies used in a bio-refinery.

The amount and the quality of the products obtained from pyrolysis are determined by the fuel used and the pyrolysis technology employed.

Depending on the objective of the pyrolysis process, different fuels can be used. For example, products with a high fixed carbon content are generally required to obtain a solid product. Moreover, the use of different technologies favours the formation of one product or another. For example, to favour the liquid fraction, pyrolysis processes uses long residence times, while to favour the formation of synthesis gas, flash processes are used; or much slower treatments and lower temperatures are used to obtain solids [74].

In recent years, the use of the pyrolysis process for the transformation of waste into energy has focused on the production of different products using slow pyrolysis [75,76], fast pyrolysis [77], flash pyrolysis [75,78], on the use of different technologies such as rotary bed, moving bed, fixed bed [79], or fluidized bed reactors [80], microwave pyrolysis [81], ablative pyrolysis or vacuum pyrolysis. Research is also being carried out on the use of different catalytic materials [82,83] Research is also being carried out on the use of different catalytic materials, such as metal-based catalyst, microporous substances or receptor catalyst, in order to improve conversion efficiency, reduce energy use, improve the yield to the final product and improve the quality of the final product, promoting the production of hydrogen [82], biochar [84] or bio-oil [79].

Future trends will be the development of new and more efficient technologies, and above all, technologies that allow large scales for the industry, enabling continuous operation, avoiding the use of batches. In addition, research on the use of catalysts has to continue in order to solve problems such as catalyst coking and catalyst regeneration. Co-pyrolysis processes, using different feedstocks and their synergism, has also to be study. Research is still needed to manage different wastes at industrial level to obtain advanced biofuels, biochar and bioproducts.

2.4. Torrefaction

Torrefaction is a thermochemical process used to upgrade waste and produce solid fuels with better quality. The process can be carried out under dry or wet conditions, or using steam. In dry torrefaction, temperatures between 200 and 300 °C are employed, and non-oxidative (inert) or oxidative atmosphere can be used. Wet torrefaction is performed at temperatures between 180 and 260 °C, using a dilute acid solution. The idea of wet roasting is similar to "hydrothermal carbonisation", which will be presented later. Steam can also be used at temperatures around 200–260 °C to improve fuel properties [85,86]. Torrefaction process produces a colour change in the waste; increase the hydrophobicity and decrease the hygroscopicity of the product; decrease the atomic H/C and O/C ratios; increase the calorific value, decrease the biological degradation; increase grindability and reactivity [85].

In recent studies, a variety of biomass waste materials have been used as feedstock in torrefaction: Lignoceluulosic biomass, energy crops, agricultural wastes or even food waste or municipal solid waste [85].

Several technologies can be used to perform the torrefaction process, depending on the fuel and the desired product. Some of the most common technologies are fixed be reactor, rotary drum reactor, screw reactor, microwave reactor, moving-bed reactor or others such as torbed reactor or belt drier.

The future trend of the torrefaction processes is the implementation of more industrial-scale plants that can cover the demand for torrefied product that currently exists [87], as well as the implementation of integrated technology as a pre-treatment to other thermochemical processes such as gasification.

2.5. Hydrothermal processes

Hydrothermal process of wastes takes place at elevated temperatures, under above-saturated pressure, which causes some reactions that alters the physicochemical properties of water and produces high-energy fuels and value-added chemicals. Hydrothermal processes perform in one or two states: subcritical water (temperatures between 100 °C and 374 °C and pressure high enough to keep water at the liquid state) and supercritical water (when water exceeds the critical point). There are three types of hydrothermal processes, regarding operating temperatures and the desired product: Hydrothermal Carbonization (HTC), when the process is at temperatures around 180 °C and hydrochar is obtained as the main product; Hydrothermal Liquefaction (HTL), when the process is at temperatures between 250 and 350 °C and biocrude-oil is obtained as the main product; and Hydrothermal Gasification (HTG), when the process is at temperatures higher than 374 °C and syngas is obtained as the main product [88].

Wastes that can be used as feedstock in hydrothermal processes can have high moisture contents, reducing the cost of drying pre-treatments needed for other thermochemical routes [88]. Food waste, plastic waste, paper waste, agricultural and forestry waste and textile waste are some examples of waste that can be used in hydrothermal processes [89–93].

Most of the studies found in the recent years have been conducted on a laboratory scale, in the form of batches, using different wastes, operating conditions and, sometimes, using catalysts [89–93]. In addition, there are some industrial-scale installations, such as those reported by the Company INGELIA, which have continuous pressurised reactors for the treatment of biomass and waste in a process that lasts between 4 and 6 h, without the use of catalysts [94].

The future of hydrothermal processes is promising, which requires further study of the use of different wastes and operating conditions, as well as the synergistic effects of using different feedstock or the integration with other WTE process such as digestion or combustion [90]. All this in order to achieve the development of efficient technologies that allow the use of hydrothermal process on an industrial scale [88].

2.6. Cracking and hydrocracking processes

Cracking and hydrocracking processes are thermochemical processes by which the hydrocarbons in the waste are broke into smaller compounds, due to the crack of C—C bonds. This process occurs at high temperatures, between 810 and 850 °C, for thermal cracking; or between 300 and 600 °C, for catalytic cracking [95]. During a hydrocracking process, the cracking of hydrocarbons is followed by the hydrogenation of the cracked hydrocarbons by reactive hydrogen to produce stable and lighter hydrocarbons. Hydrocracking facilitates the production of compounds that have higher hydrogen-to-carbon (H/C) rations than the feedstock. Hydrocracking processes commonly use catalysts and operate at high pressure levels (up to 150 atm) [96]. Cracking and hydrocracking of waste are processes that can be also performed during gasification or pyrolysis processes carried out in a fluidized bed reactor [97].

In recent years, not many wastes have been studied as hydrocracking feedstock: Plastic waste and oils are some of them. In addition, other by-products of other processes such as tar in syngas. These studies had been performed using different operating conditions and catalyst [95–98,99].

In the future, this process will be further studied for other wastes and catalysts to make a viable process. Its results seem promising for the reduction of tars from syngas from other thermochemical processes.

3. Biochemical conversion

3.1. Anaerobic digestion

Organic wastes can be efficiently processed through anaerobic digestion; a significant circular economy technology to mitigate the GHG emissions and to convert waste into biogas (50–70% CH_4) and organic fertilizers [100]. The most common organic raw waste materials used for biogas production are biodegradable organic fraction of municipal solid waste (OFMSW), sewage sludge, organic industrial wastes, food wastes and manure from livestock [32]. Depending on the moisture of raw material, wet or dry anaerobic digestion will be more suitable to process the organic waste. Wet AD is used to treat the organic matter with water content over 80% and conventionally higher than 90%, making it especially attractive for wastes as livestock manure or industrial & agriculture wastes. Continuous and batch dry AD is typically used to process materials with high solids content, between 20% and 40% [30], which is more suitable for the treatment of the organic fraction of municipal solid waste and agricultural wastes. Wet AD leads to methane yields of 0.1–0.150 m3/kg of waste while dry AD presents methane yields between 0.2 and 0.6 m3/kg of volatile solids [33]. Dry AD has increased its interest and capacity in the last decade, but the lack of knowledge compared to well-established wet AD technology makes it still less preferred and represents only a 35% of anaerobic digestion facilities [33]. Besides total solids content of feedstock, other significant differences between wet and dry AD include: (i) not requirement of internal mixing in dry AD digestors, (ii) dry AD can be continuous or batch process, being batch with percolate recirculation the preferred configuration or (iii) the requirement of water is scarce or none in dry AD.

The most relevant aspects for the efficiency and productivity of this process has been identified as: feedstock composition, co-digestion of substrates, temperature, pH, C/N, organic load and hydraulic retention time [32]. The composition of substrate strongly varies the methane production; between 0, 33 and 450 Nm^3 biogas/ton VS (volatile solids) depending on the use of lignocellulosic wastes or sugar and starch crops [34]. Co-digestion of complementary substrates provides an enhanced equilibrium of macro and micronutrients which improves biogas production by increasing the biodegradable components, providing a wider range of digesting microbial species and increasing the concentrations of active biomass [11]. Further research in **co-digestion** options must be carried out to stimulate the degradation of organic matter and to strengthen the microbial metabolism. **Pretreatments** remove unwanted compounds and enhance biodegradability of the waste. Lately, several pretreatments were explored to improve biogas production between 20 and 33% [101]. They include physical (grinding/milling, irradiation), physico-chemical (steam explosion, liquid hot water), chemical (alkali, acid, oxidizing agents, organic solvent) or biological (ammonia fibre explosion, ionic liquids or fungal).

Domestic solid waste production rate is rapidly increasing worldwide with food and green waste contents between 32 and 56% depending on the GDP of the country [33,34]. Dry anaerobic digestion has received increasing attention as a potential technology to reduce the GHG emissions of this waste and it has been shown that the rate-limiting step is the hydrolysis phase. Future research in this line should explore some of the different pretreatment options presented above to enhance hydrolisis through the increase of biodegradability of these wastes keeping in mind the cost-effectiveness of the process.

The trend in developed and developing countries is to move towards intensive livestock farming leading to higher specific concentrations of **livestock manure** with strong environmental impact when not properly managed. The main limitations of manure as feedstock for anaerobic digestion are the low C/N ratio (given its high nitrogen content), the low percentage of volatile solids and the high proportion of components with low degradability potential. Research should focus on innovative biological, chemical, thermal and physical pretreatments for livestock manure to further enhance methane production [41].

Sewage sludge represents a major issue in wastewater treatment plants and anaerobic digestion appears as a well-known and suitable technology to process it [42]. Urban wastewater treatment facilities supply a large share of the current worldwide produced biogas also presenting a great potential for future exploitation [43]. This process makes use of primary and secondary sludge converting about near 50% of organic matter in the sludge into biogas.

Lignocellulose is an interesting substrate for second-generation biofuel production given its low cost and wide availability. However, it also presents a complex structure which limits its biological degradation [102]. Physical, physical-chemical, chemical and biological pretreatments are used to modify this structure increasing its biodegradability. Codigestion of lignocellulosic residues with high C/N ratio is commonly carried out. Low yields of biogas associated to lignocellulose wastes can also be improved through the application of o physical and physico-chemical pretreatments.

Waste food represents one third of food production, around 1.6 Gt/year, and anaerobic digestion appears as an adequate technology to efficiently dispose fruit or vegetable given their high moisture and high biodegradability [103]. Their easy hydrolysis generates acidification which inhibites methane production reducing final efficiency. Acidification can be solved by means of different pretreatments, co-digestion, adjustment of the inoculum concentration and monitoring of the operation conditions [104].

Traditionally, the application of anaerobic digestion is limited to **industrial wastewater** with COD of 3000–40,000 mg/L such as vegetable and fruit, starch, sugar and alcoholic beverages industrial sectors. In the last years, wastewater with lower COD (1500–3000 mg/L) has also been successfully processed by specific anaerobic digestors [46].

Photosynthetic eukaryotic and prokaryotes **microalgae** comprise over 20,000 species whose composition contains carbohydrates, proteins and lipids with varying content of volatile solids. The main drawback of anaerobic digestion of microalgae is the low biodegradability of unprocessed microalgae. This problem is solved through the application of pretreatments which break down the cell walls of the microalgae, increasing biomass biodegradability and methane yields [47]. A second limitation is the low C/N ratio and/or ammonia inhibition, which can be counterbalanced through the addition of high carbon substrates [48].

Anaerobic digestion of organic waste is considered a reliable process and has become an attractive technology from a policy-making point of view which will play a major role [105]. Also standardization process should be promoted by governments to boost the utilization of low carbon biogas for energy generation [106]. Finally, economic feasibility of this technology should be carefully assessed given the large investments required. Further research should focus on the finding additional revenues of the process from the chemical products.

3.2. Fermentation

Anaerobic digestion and fermentation are similar processes that involve the breakdown of organic matter by means of microorganisms. However, anaerobic digestion occurs in an oxygen-free environment, while fermentation can occur in the presence or absence of oxygen. The outlet composition of this process will depend on the catalyst used, the organic substrate (sugars, starches, cellulose) and the operating conditions. In the last years, microbial anaerobic fermentation has become a promising technology to achieve high yields of hydrogen production together with other organic alcohols and/or acids. Depending on the requirements of light for the microorganisms (bacteria, yeasts, and fungi), fermentation can be classified as: (a) dark fermentation and (b) photo fermentation [107].

Dark fermentation is carried out under dark anaerobic conditions, where breakdown of cellulosic organic feedstock results in the production of biological hydrogen along with organic acids and alcohols [29]. Special interest is observed in **hyperthermophilic bacteria** (*Thermotogaceae*) which metabolize complex sugars into hydrogen through dark fermentation [108]. The extreme temperatures required for the growth of these bacteria reduce organic contamination and also facilitates the solubilisation of the substrate. Photofermentation makes use of **photosynthetic bacteria** which also produce biohydrogen from organic matter under sunlight and anaerobic conditions [109]. Recently, the integration of both two fermentation process has been proposed to improve hydrogen production yield. The main drawback of these processes is the low energy conversion efficiency i.e. around 4–5% [110]. The great challenge for organic waste fermentation is, therefore, the low hydrogen production rate and yield.

Other emerging technologies in the field of fermentation which are prone to increase efficiency, reduce costs, and increase sustainability include (i) **microbial electrolysis** [111], which increase the yield of biofuels reducing the amount of carbon dioxide released, (ii) **synthetic biology** [112], which involve the application of genetic engineering to design specific improved microorganisms for specific types of waste, (iii) **solid-state fermentation** [113], which is fed by solid substrates, such as agricultural waste or food processing byproducts, reducing the liquid handling and increasing efficiency, or (iv) **membrane bioreactors** [114], which use membranes to separate microorganisms from the fermentation broth, increasing efficiency and reducing the downstream processing.

Also the investigation of different **substrate pretreatments** (mechanical, thermal, chemical, and biological) [108,115] and **co-fermentation** of different substrate (balance nutritional demands) are hot aspects which will lead to more sustainable and cost-efficient processes. Future efforts in co-fermentation should focus on the regulation of macronutrients as C/N ratio, the understanding of the parameters controlling the production of volatile fatty acids and the exploration of continuous co-fermentation facilities instead of batch experiments [12].

4. Chemical conversion

The transesterification of oil-based materials is the most widespread chemical conversion process to obtain biodiesel as energy product from oil wastes [19], being a smooth and economic processing [16]. The chemical process via transesterification is based in an organic reaction in which a low molecular weight alcohol (e.g. methanol or ethanol) reacts with the lipids content in the oil based source (triglycerides) in the presence or absence of catalyst. The organic reaction form biodiesel (e.g. fatty acid methyl ester (FAME) or fatty acid ethyl ester (FAEE) and glycerol as by-product [116]. Among other chemical procedures to transform oil-based feedstocks into biofuels, the hydrogenation of vegetable oils (HVO) is a promising technology for renewable diesel production [23]. The HVO process lies in a catalytically hydro-treatment of triglycerides or fatty acids from an oil-based material at high temperature (300–390 °C) [24], obtaining a chemical composition based on oxygen-free hydrocarbons [117]. The obtained renewable diesel from HVO production technology presents advantageous properties compared to biodiesel from transesterification (i.e. lower NO_x and CO_2 emissions, calorific value close to fossil fuels, higher cetane number [118]). Even HVO renewable diesel from HVO process is suitable for use in aviation as a jet fuel, given its (i) high calorific value, (i) low viscosity and (i) zero oxygen content [52]. Moreover, current fossil-fuel refineries could be re-constructed to produce renewable biodiesel from HVO production technology [24], being the most cost effective way to process low cost oil-based feedstocks [53] using the same elements of a fossil fuel refinery (catalyst, reactor type and separation equipment) [98]. The renewable diesel can be directly combusted in current diesel engines [23], adjusting some parameters to take advantage of its full potential [119]. Once the investment costs of stand-alone HVO facilities will decrease [24,53], as well as the production of the required hydrogen in the process comes from 100% renewable sources [120], HVO production technology could be the dominant one in the production of renewable diesel, which shares similar properties to fossil diesel [23].

The biodiesel production can be classified as a function of the feedstock used: edible vegetable oils, non-edible vegetable oils, waste oils and animal fats [121]. **Edible vegetable oils** comprehend the first-generation raw materials to produce biodiesel and suppose 60–80% of the biodiesel production cost. The competition between human consumption and fuel production promoted the development of second generation of biodiesel [122,123]. The second-generation biodiesel is obtained from **non-edible vegetable oils**. However, the farming land use to produce non-edible raw material reduce the land use for food production. Besides, the high alcohol requirement for transesterification process and the low oil yield obtained from non-edible raw materials implies the search of new oil sources for biodiesel production [124,125]. The third-generation feedstocks are **low-cost, non-edible and biological sources** allowing environmental sustainability and reduction of biodiesel production costs [122]. Two types of feedstocks are considered in the third category: **algae oils and waste oils**. Besides wastewater treatment, the microalgae cultivation can produce lipid-rich biomass as feedstock for biodiesel production by transesterification [126]. Recent research focus on the process optimization, maximizing the productivity to reduce operating costs. The continuous operation compared to the batch operation yields more positive results, obtaining a larger production of biomass with a high lipid content [127]. The production of lipid-rich biomass from algae could be compatible with the production of biomethane production by an upgrading biogas system, contributing to the sustainability of the process [128] and the climate change mitigation through carbon capture [129]. Thus, the algae could be a promising oil-based material for biofuel production in the long-term, after minimizing costs and improving the efficiency of the current process [127]. However, the waste oils are low-cost and high-availability raw materials. Thus, waste oils can be a suitable raw material for biodiesel production minimizing 60–70% the process cost [20] and waste oil disposal problems [130]. Transesterification of waste oil-based materials can occur catalytically or without catalysis. Table 2 show various reaction parameters related to scientific investigations developed in recent years.

Most of the waste oils comes from edible oils processed by cooking or frying. The collection of waste cooking oils (WCO) is carried out in households, restaurants, and food processing industries [16]. The WCO collected usually contains high concentration of free fatty acids (FFA), water and solid impurities hindering the biodiesel production. The saponification and hydrolysis process taking place during transesterification reduce biodiesel conversion [22]. The catalyst used in the transesterification of waste oil determines whether or not a previous pre-treatment is necessary to improve the biodiesel yield. Literature in the last three years has focused on the development of the following catalysts: (i) enzymatic catalysts without waste oil pre-treatment, (ii) homogeneous catalysts with a previous stage of waste oil treatment, (iii) heterogeneous catalysts synthesized from waste or abundant materials in nature, (iv) heterogeneous nanocatalysts and (v) supercritical methanol method without catalyst use. The enzymatic biocatalysts can form esters from FFA and perform the transesterification process simultaneously, without a previous treatment of the waste oil. The biodiesel yield achieves under biocatalysis transesterification are between 93.8% and 98.76% with low alcohol/oil molar ratio and reaction time from 5 to 10 h at near room temperature [131–133]. Regarding homogeneous catalysis, a previous acid-based esterification process is required to perform the transesterification. An alkali homogeneous catalyst is used during the transesterification assisted by microwave power or ultrasound power to reduce the energy consumption. The alcohol/oil molar ratio is similar to the biocatalysis transesterification. However, the

Table 2
Different operation parameters associated to transesterification of waste oil in recent literature.

Waste oil	Catalyst	Catalysis type	Alcohol/oil molar ratio	Reaction temperature (°C)	Time reaction (h)	Biodiesel yield (%)	Ref.
Sunflower waste cooking oil	Lipase from *Araujia sericifera* (0.05%)	Enzymatic Biocatalysis	0.2:1	25	10	90 – 98	[131]
Waste rapeseed oil	Free lipase from *Thermomyces lanuginosus* (9.7%)	Enzymatic Biocatalysis	5:1	25	5	98.76	[132]
Waste phoenix seed oil	Free lipase *Thermomyces lanuginosus* (9.7%)	Enzymatic Biocatalysis	4.3:1	31	6.9	93.8	[133]
Solid food waste oil	KOH (1.28%)	Homogeneous	6.08:1	52.5	0.67	93.23	[49]
Waste cooking oil	NaOH (2%)	Homogeneous	5:1	65	0.5	94.6	[134]
Restaurant waste oil	Fe/Sílica (1.2%)	Heterogeneous	6:1	60	1.5	99.73	[50]
Waste canola oil	Lithium/zinc chicken bone (4%)	Heterogeneous	18:1	60	3.5	98	[135]
Waste cooking oil	Limescale deposit	Heterogeneous	2.15:5	60	0.21	97.16	[136]
Waste frying oil	Zinc modified pumice (3%)	Heterogeneous	12:1	60	1 to 3	91.05	[137]
Waste cooking oil	Clay/CaO (9.6%)	Heterogeneous	1:1.94	54.97	1.24	97.16	[138]
Waste cooking oil	Char from pyrolysis eggshells (10%)	Heterogeneous	12:1	65	3	96.9	[139]
Waste frying oil	Zeolite-chitosan composite (1%)	Heterogeneous	8:1	25	0.5	96.5	[140]
Waste cooking oil	Green alkali modified clinoptilolite (4%)	Nanocatalysis	16:1	70	2.5	98.7	[141]
Waste cooking oil	Sulfonated solid acid (15%)	Nanocatalysis	18:1	60	0.25	89.19	[142]
Waste edible oil	Waste chicken eggshells (4.571%)	Nanocatalysis	16.7:1	69.37	7.08	98.37	[143]
Waste cooking oil	Waste eggshells (5%)	Nanocatalysis	20:1	65	4	96.74	[144]
Waste cooking oil	Na_2O impregnated on carbon nanotubes (3%)	Nanocatalysis	20:1	65	3	97	[145]
Fish waste oil	Supercritical methanol (w/o catalyst) $P = 112.7$ bar		22.3:1	270	-	95.2	[51]

reaction time is below 1 h and temperature during the process may reach 65 °C, getting a biodiesel conversion of 93.23% for transesterification assisted by ultrasound [49] and 94.6% under microwave power [134]. Moreover, the heterogeneous catalysts are the most investigated in recent literature of waste oil-based transesterification. The major advantage is the reusability of the homogeneous catalysts without significant loss of activity. However, the reaction time and temperature required for transesterification is greater than homogeneous catalysis. Nevertheless, the use of co-solvents during the reaction, such as acetone [136,140] or toluene [138], improve the biodiesel conversion around 97% and reduce the reaction time and temperature, even at room temperature when transesterification is assisted by electrolysis [140]. Notably, the latest research works are aimed at the development of low-cost heterogeneous catalysts synthetized from natural resources, such as eggshells [139], chicken bone [135], pumice stone [137] or highly available sources such as anthills [50], achieving a high yield of biodiesel over 91%. Besides the previous catalysts, current research lines are directed towards the synthesis of heterogeneous nanocatalysts. Mainly these nanocatalysts come from waste or abundant materials, such as chicken eggshells [143,144], sugarcane bagasse [142] or green tea extracts [141]. Other studies use simple and green techniques for the synthesis of the nanocatalyst [145]. The use of waste oils as raw material and waste-based nanocatalyst for transesterification process reduces the cost of biodiesel production and contributes to the recovery of waste materials. However, the nanocatalysis requires a high alcohol/oil molar ratio and a reaction temperature over 60 °C to achieve 96–99% of biodiesel conversion after a transesterification reaction lasting from 2.5 to 7 h. Nevertheless, the reaction time can be reduced to 0.25 h sacrificing the biodiesel production efficiency below 90% [142]. The last type of transesterification allows the absence of catalyst instead of increasing alcohol consumption. Research in this area is scarce due to high energy consumption (high temperature and working pressure are required). Simin Espootin et al. achieved a biodiesel yield of 95% from waste fish oil using hexane as co-solvent at 270 °C and 112.7 bar [51].

The transition towards renewable energies in the medium term should be matched with the progressive replacement of fossil fuels by biofuels to avoid an energy crisis in the near future [125]. Therefore, the third-generation biodiesel production from waste sources can be one of the most viable alternatives from an economic and sustainable point of view. The final objective of the most recent research is focused on reducing the cost of biodiesel production by complying with limits established by different standards (e.g. ASTM). The reduction of the biodiesel production cost can be achieved through the use of: (i) waste oils from different sources, (ii) waste or high-availability and low-cost natural sources for the synthesis of catalysts and (iii) reusable catalysts without significant loss of activity. Regarding transesterification process, the research interest of a single-step heterogeneous or enzymatic catalysis of waste oil is growing to avoid waste oil pre-treatment. However, the two-step transesterification assisted by low-energy supply with a previous esterification of waste oil can reduce the reaction time and energy consumption being a good candidate for commercial scale.

5. Waste biorefinery

The integration of energy conversion processes or the valorization of a single or multiple waste in the same facility could solve economic issues of WTE. The biorefinery concept is defined as a sustainable biomass processing to obtain value-added products and energy. Biorefineries must be part of the circular economy, promoting climate change mitigation and waste valorization [146]. Moreover, the local waste availability and the conversion technologies sustainability influences the technical and economic feasibility of a biorefinery facility [147]. The second generation biorefineries are focused on organic and lignocellulosic waste feedstocks, being able to integrate one or several processes to obtain different products through a single or multiple residues (i.e. integration by (i) feedstock, (ii) products, (iii) platforms and (iii) conversion processes) [148]. A novel heterogeneous mixture of sewage sludge and food waste is used in a feedstock integration biorefinery to obtain biomethane as final product, being physically, chemically and biologically pre-treated. Firstly, a dark fermentation of the pre-treated feedstock produces volatile fatty acids, which are the source of an anaerobic digestion process to produce biogas. Biomethane is obtained from biogas through an innovative bioelectrochemical upgrading process [149]. The biorefineries integrated by products are mainly aimed at obtaining gaseous biofuels from a mixture of agricultural residues. Anaerobic digestion is used as the first process to obtain biogas as the first final product. The digestate from anaerobic digestion is subjected to a second air gasification process in a downdraft fixed-bed reactor to obtain syngas, which may be suitable for the electricity production [68]. Several energy products can be obtained from lignocellulosic wastes in a biorefinery designed by platforms. A three-platform (pyrolysis oil, syngas, electricity and heat) biorefinery is able to produce electrical and thermal power and biofuels from straw, using as conversion processes fast pyrolysis, oxygen gasification and combustion [150]. The organic fraction of municipal solid waste can be fractioned to obtain different products through several independent processes in a biorefinery integrated by conversion processes. One pre-treatment fraction can produce bioethanol after being subjected to hydrolysis and fermentation processes. An anaerobic digestion of the rest of the municipal organic waste produce (i) volatile fatty acids as an intermediate product for obtaining bioproducts and (ii) biogas, which is upgraded to obtain biomethane and other bioproducts [151].

The future trend of waste biorefinery will be based on the efficient integration of feedstocks, energy consumption and conversion processes. The integration of thermochemical, biochemical and chemical conversion processes into a biorefinery facility will be able to produce biofuels and other energy products, minimizing issues such as waste disposal and intermittent feedstock supply [148]. The waste feedstock characterization and the selection of suitable pretreatments could enhance the energy and economic efficiency of an integrated biorefinery.

6. Final remarks

The future trend for WTE processes is that they will be used more and more often and in an increasingly sustainable way. In this sense, for example, some European policies favour the promotion of the use of waste and bioenergy for heating and cooling, including the use of district heating. More electricity generation is also favoured by promoting the high efficiency of combined heat and power plants. Biofuel production is encouraged, with the gradual phase-out of indirect land-use change and promoting the generation of advanced biofuels, as well as renewable hydrogen.

In thermochemical processes, the trend is towards the use of the biorefinery concept. Due to the fact that waste is a renewable source of carbon, it must be utilised in the same facility, through recovery or recycling, obtaining products with greater added value. Other energy streams, in the form of thermal or electrical energy or in the form of biofuels such as hydrogen, can be obtained.

The future outlook of anaerobic digestion is related to the potential to transform high loads of organic matter feedstocks. In this sense, its integration with other processes with the aim of developing biorefineries represents a very interesting alternative. Besides, the economics of pre-treatment units (including transport costs, price and market oscillations, energy demand and O&M costs) will be a key aspect to achieve the feasibility of anaerobic digestion in future scenarios. Besides, the development of promising batch dry AD is currently focused on the optimization of feedstock composition and size, inoculum to substrate ratio, liquid recirculation, bed compaction and use of bulking agents to limit inhibition effects and process instability [33].

Dark fermentation appears an excellent path for biohydrogen production. Research must focused on the development of robust microorganisms with significant cellulolytic properties to improve the economic feasibility of biohydrogen production [152].

With regard to chemical conversion of wastes, research efforts should be carried out in the field of waste oil management and biodiesel yield creating a global policy on effective waste oil collection and improving biodiesel conversion keeping economic viability of the process, respectively.

Finally, highlight the importance of the waste characterization before their energy recovery. A proper waste management and classification promotes the selection of the most suitable conversion pathways and final energy products, as well as the integral design of a waste biorefinery. Operational strategies focused on (i) the requirements from feedstocks to final products and (ii) the definition of proper energy conversion processes could be implemented in a waste biorefinery to be technically and economically feasible.

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Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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