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REVIEW

Application of waste biomass for the production of biofuels and catalysts: a review

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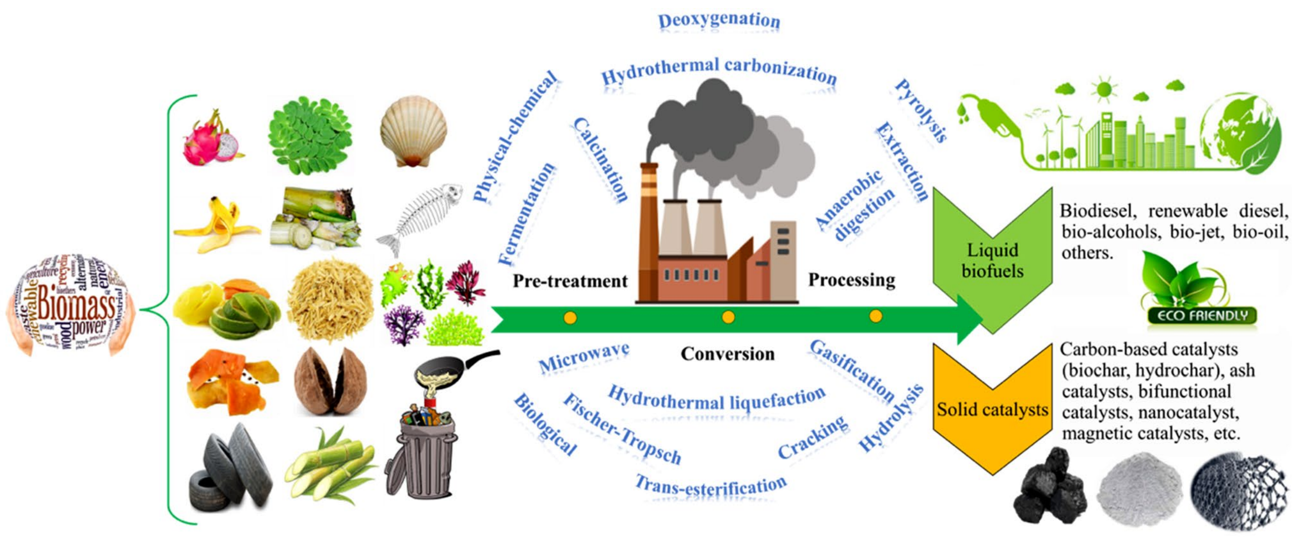
Abstract

Sustainable development is imperative, and the worldwide energy production must focus on the transition from petroleum derivatives to biomass-based biofuels and bioproducts to achieve a bio-based economy. The global interest in the processing of waste biomass to obtain bio-based products is continuously increasing. However, biorefineries have not yet been consolidated. The effective conversion of biomass components for the generation of value-added biochemicals and biofuels is a determining factor for the economic success of biorefineries. Therefore, exhaustive research has been performed to consolidate the biorefinery industry. This review summarizes the current advances in liquid biofuel production and solid catalysts prepared from waste biomass, as well as their advantages, drawbacks, and statistical data. It offers an extensive perspective, covering conventional methods and cutting-edge techniques such as biochemical and thermochemical biomass conversion technologies (e.g., hydrolysis, fermentation, pyrolysis, and gasification) to produce bioalcohols, biodiesel, renewable diesel, bio-jet, and bio-oil. In addition, the preparation of heterogeneous catalysts using residual biomass and different synthesis routes and their role in biofuel production were analyzed. This review contributes to the analysis of the importance of identifying and valorizing a wide spectrum of raw materials (i.e., urban, forestry, industrial, and agricultural) that have the potential to be used as catalyst precursors and biofuel feedstock. Finally, a techno-economic analysis, the main challenges, and the future scope of the diverse methods used to prepare biofuels and catalysts are discussed. This review examines numerous aspects from biomass to catalysts, thus providing relevant information for researchers, students, policymakers, and industry experts.

Graphical abstract



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Keywords Bioenergy · Liquid biofuels · Solid catalysts · Waste biomass · Biomass conversion · Sustainability

Introduction

The accelerated and growing exploitation of fossil-based fuels is associated with population expansion and industrial and economic development (Nanda and Berruti 2021), which have also intensified energy and environmental problems, thus becoming the main concern that humanity faces today. Different statistics indicate that natural gas, coal, crude oil, and other fossil fuel derivatives (Wang et al. 2022c) represent more than 80% of the total energy production worldwide (Davidson 2019). Transportation, agriculture, and almost all industrial sectors are highly dependent on the use of fuels obtained from nonrenewable sources (Wang et al. 2022c). These fuels have been subjected to a drastic depletion because of the continuous increasing energy demand of society, in addition to generating greenhouse gas emissions that influence climate change, deteriorate ecosystems, and cause potential risks to human health (Wu et al. 2023). Therefore, this has driven the scientific community to find alternative sources of low-cost, sustainable, and renewable energy (e.g., wind, hydraulic, solar, and biomass) (Shahbeik et al. 2022).

A perspective of sustainable development is imperative in this direction, where cost-effective implementation and operation of biorefineries are key factors in the transition from a linear to a circular economy. The installation and start-up of biorefineries have promoted biomass valorization at local and regional levels to maximize its environmental and economic benefits, thus generating a variety of competitive and efficient technologies for biomass conversion into value-added products, see Fig. 1. Biomass obtained from industrial, agricultural, and urban sources is a low-cost feedstock for the production of fuels and chemicals, owing to its wide availability, non-edible nature, and carbon–neutral

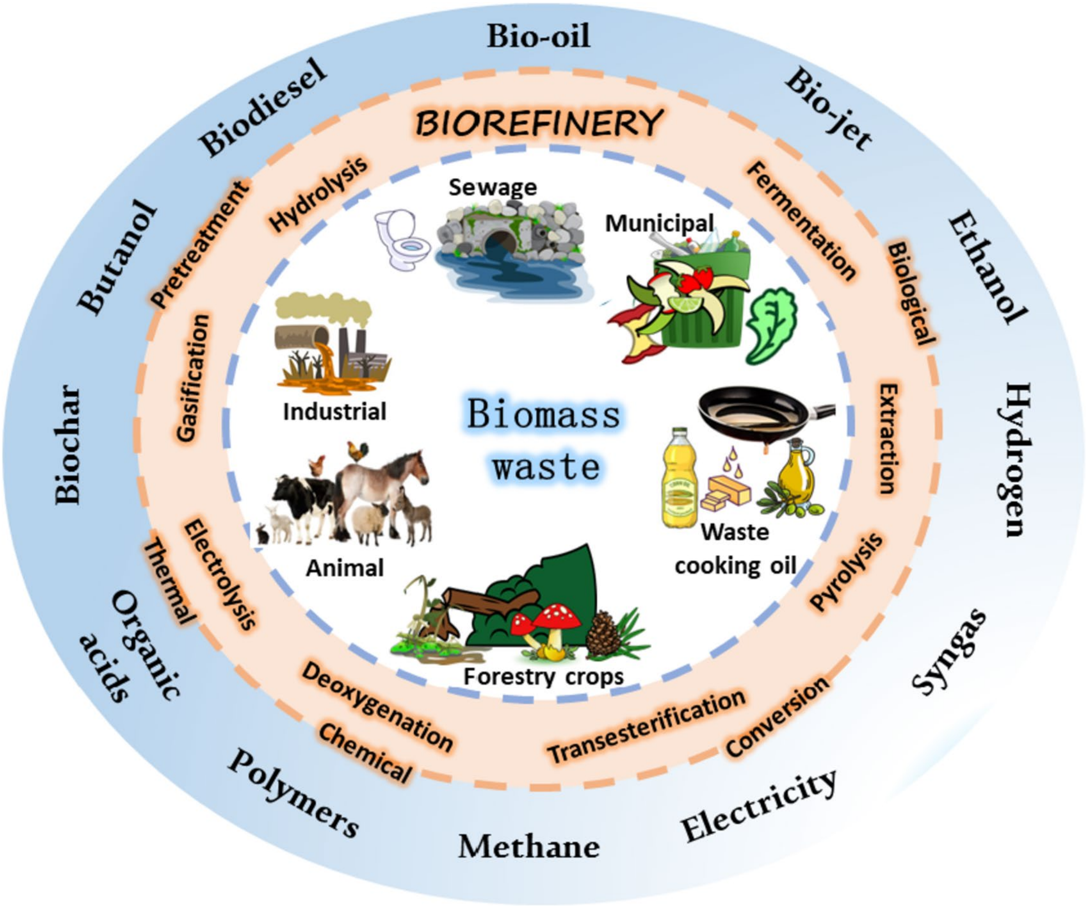


Fig. 1 Biomass wastes, biorefinery processes and their products

property (Singh et al. 2022). Biofuels have become one of the main sources of green energy and are considered promising substitutes for fossil fuels because of their economic and environmental benefits (Li et al. 2022b).

Herein, it is convenient to remark that several technologies for the thermochemical transformation of biomass also rely on reactive systems that must be catalyzed (Ahmed et al. 2022a). Therefore, the development of heterogeneous catalysts derived from biomass has become increasingly important, because they are essential for the production of biofuels and other value-added materials (Hussain et al. 2022). They can enhance the reaction rates, improve selectivity, and provide more efficient conversion of biomass feedstock into biofuels and other chemicals. Note that high biomass conversion is crucial to successfully achieve a competitive bioeconomy in which the catalysts play a key role in the quality of biofuels and other products (Abdullah et al. 2022). The application of carbon-derived supports in catalyst preparation has been widely studied (Abdullah et al. 2022) and ongoing research is focused on developing new materials with better properties to further advance the consolidation of a biomass-based economy (Zou et al. 2022).

In this review, the advantages and drawbacks of liquid biofuels (e.g., biodiesel, renewable diesel, bioalcohols, bio-oil, and bio-jet) obtained from biomass processing are discussed and analyzed. The importance and relevant statistics of the residual biomass used to produce these liquid biofuels are highlighted. A comprehensive overview of the conventional and well-studied cutting-edge techniques is also provided. In addition, the preparation and application of biomass-based catalysts and their utilization in obtaining biofuels are discussed. A summary of recent studies on the preparation of biofuels and catalysts derived from biomass is presented. The inclusion of a techno-economic analysis, challenges, and perspectives amplifies the scope of this review. These insights, combined with thought-provoking remarks, not only enrich the understanding of this subject, but also pave the way for future innovations.

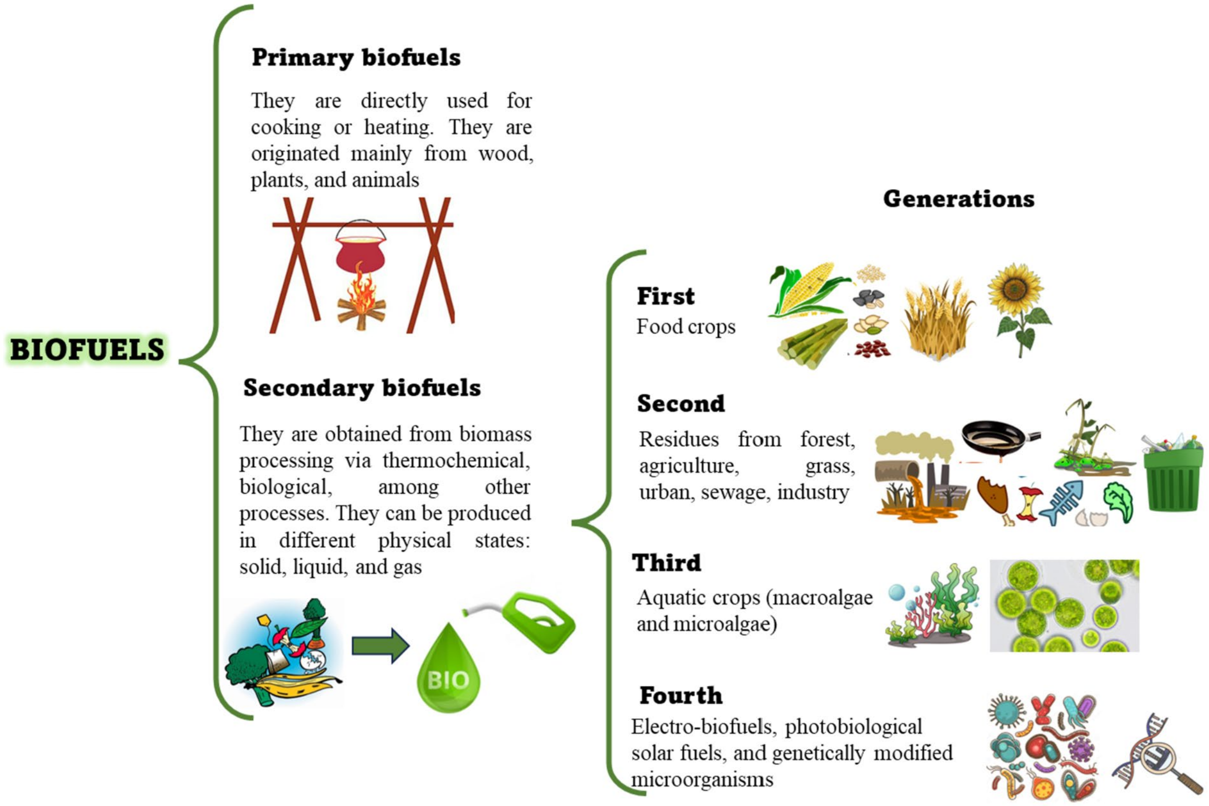
This review is a meticulous examination of multiple facets, from biomass to catalysts, and its forward-looking approach makes it a useful resource for researchers, students, policymakers, and industry experts.

Biofuels: their advantages and drawbacks

Biofuels have been defined as all types of energy derived from renewable biological sources (e.g., organic, agricultural, industrial, urban, forestry, human, and animal wastes) (Powar et al. 2022). Overall, biofuels exhibit a competitive cost-effectiveness tradeoff during energy production. Biofuels are easy to handle and store because of their low flammability and toxicity compared with fossil fuels (Priya et al. 2022). Various studies have concluded that biofuels are distinguished for being environmentally friendly and sustainable due to their degradation properties, especially because they emit harmful gases into the atmosphere by 10 times lower than fossil fuels during their consumption (Angulo-Mosquera et al. 2021). They are classified as primary or secondary biofuels, as shown in Fig. 2. Primary biofuels are used directly without pretreatment for cooking or heating, and they mainly originate from wood, plants, and animals (Ahmed et al. 2023). Secondary biofuels are obtained from biomass processing where thermochemical (i.e., transesterification) biological (i.e., fermentation) routes or catalysts are required (Ahmed et al. 2023). Biofuels can be produced in different physical states: solid, liquid, and gas (Priya et al. 2022).

Depending on the type and source of the raw materials used to produce biofuels, they can be categorized as first- to fourth-generation fuels (Priya et al. 2022). First-generation biofuels are obtained from edible raw materials such as high lipid-containing seeds [e.g., soybean (Vázquez-Garrido et al. 2021), neem (Adepoju 2020), palm (Basir et al. 2019)], sugar cane (Rabiu et al. 2018), sugar beet (Del Amo-Mateos et al. 2022), potato (Chohan et al. 2020), sorghum (Batog et al. 2020), wheat (Gouran et al. 2021), corn (Dai et al. 2019), among others. One of the main limitations of this generation of biofuels is the significant investment in terms of capital, energy, and time to obtain the raw materials (food crops), in addition to their negative impact on the food sector, which has generated conflict and debate in the world population because they could become scarce due to fluctuations and instabilities in market prices (Astolfi et al. 2020; Liu et al. 2021). Second-generation biofuels are produced from non-edible sources (Puricelli et al. 2021), lignocellulosic biomass (Ahorsu et al. 2018), residues [e.g., forestry (Liu et al. 2015), agricultural (Wei et al. 2022), industrial (Tekin et al. 2023), and urban (Zhang et al. 2019)], used cooking oils (Abdullah et al. 2022), and animal fat (Adepoju 2020). In particular, lignocellulosic biomass, owing to its abundance and easy availability, makes second-generation biofuels the most interesting alternative. These feedstock sources make biofuel production more economical, effective, sustainable, and environmentally friendly (Lin and Lu 2021). However, it is well-known that second-generation biofuels may not be entirely profitable, as the equipment and technologies required to obtain commercial products that meet established quality standards are typically expensive (Liu et al. 2021). It has been recognized that another factor that could impact the production costs of second-generation biofuel manufacturing processes is the potential shortage of raw materials (Puricelli et al. 2021; Abbaszaadeh et al. 2012).

On the other hand, third-generation biofuels are generally based on the implementation of aquatic crops (e.g., microalgae) as feedstock (Choi et al. 2019). One of the main



They are directly used for cooking or heating. They are originated mainly from wood, plants, and animals

They are obtained from biomass processing via thermochemical, biological, among other processes. They can be produced in different physical states: solid, liquid, and gas

Residues from forest, agriculture, grass, urban, sewage, industry

Aquatic crops (macroalgae and microalgae)

Electro-biofuels, photobiological solar fuels, and genetically modified microorganisms

Fig. 2 Classification of biofuels and their generations

properties that algae present and stand out over other energy sources is its high lipid and nutrient content, which makes it an attractive alternative for biofuel production (Srivastava 2019). Another benefit of this energy source is its high performance in capturing greenhouse gases (CO_2), easy adaptability, rapid growth in different water bodies (i.e., wastewater, freshwater, and seawater), and high photosynthetic efficiency (Choi et al. 2019; Aron et al. 2020).

Recently, fourth-generation biofuels have been developed from electro-biofuels, photobiological solar fuels, and genetically modified microorganisms (e.g., microalgae, cyanobacteria and yeast) (Malode et al. 2022). These microorganisms not only enhance the photosynthesis process and wastewater treatment, but also demonstrate their ability to consume high concentrations of CO_2, compared to other raw materials (Leong et al. 2019). This in turn facilitates biofuel production and promotes environmental conservation. These modified photosynthetic feedstocks are renewable, inexpensive, widely and easily available (Abdullah et al. 2019). It is worth mentioning that despite the progress achieved in this generation of biofuels, they are still in the development phase without reaching large-scale commercialization and industrial implementation (Puricelli et al. 2021).

Liquid biofuels have high energy density and are alternatives to conventional fuels used in aviation (Vamvuka 2011) where petroleum-derived liquid fuels play a key role, whereas gaseous biofuels (i.e., biomethane and biohydrogen) offer greater benefits for public transportation and industrial combustion (Priya et al. 2022). Solid biofuels derived from waste biomass require low energy consumption for their production and have, by nature, a high calorific value in comparison with nonrenewable solid energy sources (i.e., firewood, charcoal, and lignite) that are commonly utilized to meet daily human needs (Angulo-Mosquera et al. 2021).

As stated, the biofuel industry, based on renewable feedstocks, has the potential to substitute petrochemical industries, with the consequent creation of new employment opportunities, and can contribute to the implementation of a circular economy for future generations (Powar et al. 2022). However, it is necessary to overcome the drawbacks of current biofuel production processes. This requires confronting the economic, environmental, social, and technical barriers inherent to each type of biofuel generation with the aim of consolidating profitable large-scale exploitation and commercialization in the near future (Kothari et al. 2020). It should be noted that there are still concerns regarding the production costs of some biofuels, which could be higher than those of conventional fuels (Angulo-Mosquera et al. 2021). At present, the management, transportation, and feedstock costs are considered obstacles to producing biofuels at an industrial scale under specific socioeconomic conditions (Angulo-Mosquera et al. 2021). In some cases, large extensions of land are required, which can lead to deforestation, habitat destruction, and competition with food crops; however, the consequent water consumption generates environmental pollution and potential scarcity (Mahapatra et al. 2021; Priya et al. 2022). The overall energy balance and greenhouse gas emissions of biofuels can vary significantly, depending on the feedstock and production process. Some industrial processes require a large amount of energy to carry out the biofuel synthesis or can be technologically challenging and costly (Angulo-Mosquera et al. 2021). It has also been proven that the chemical properties of some biofuels can damage and impact the performance of internal combustion engines during long-term operation (Priya et al. 2022). Therefore, there are still several technological challenges to achieving successful large-scale incorporation of biofuels in the global market.

In summary, the economy of biofuel production can be influenced by factors such as feedstock costs, energy inputs, and government subsidies, which can affect the competitiveness of biofuels compared to other conventional energy sources. It is important to consider these disadvantages alongside the potential benefits of liquid biofuels to generate better technologies for their production. The ongoing research and technological efforts have focused on addressing these challenges to improve the sustainability of biofuel supply chains and exploring alternative feedstocks and processes to overcome the fact that the global economy continues to rely heavily on fossil fuels.

Biomass waste: sources, classification and statistics

Biomass is a well-known renewable energy source that has become the focus of producing not only thermal or electrical energy, but also biofuels (e.g., ethanol and biodiesel) and other high value-added chemical products (e.g., furfural and levoglucosan). It is considered to be an environmentally friendly, cost-effective, and sustainable feedstock (Patra et al. 2022).

The main sources of biomass are wood, crops, and different agricultural, forestry, urban, animal, and industrial wastes (Palmisano et al. 2022). They can be classified into four major groups according to their main components: sugar, starch, triglycerides, lignocellulose, and hydrocarbons (pyrolysis oil) (Goswami et al. 2022).

Lignocellulosic biomass obtained from agricultural residues has been the subject of recent studies because of its high calorific capacity; in particular, there is an alternative to provide adequate use and eliminate the large loads generated and accumulated globally (Zhang et al. 2020a). This type of biomass is considered a valuable energy source for the production of biofuels and green value-added chemicals because of its renewable nature and wide availability (Koul et al. 2022). Lignocellulosic biomass is mostly composed of biopolymers (cellulose, hemicellulose, and lignin) (Li et al. 2022a), whereas inorganic minerals and organic extractives are found in trace amounts (Vassilev et al. 2012). The composition of this biomass can vary depending on its source and origin (Ramos et al. 2022). It has been estimated an annual production of 181.5 billion tons of lignocellulosic biomass, of which only 8.2 billion tons are used for practical purposes and different final applications (Dahmen et al. 2019).

It is important to highlight that food waste deserves special mention because it is a valuable raw source for biofuel production. Food waste is generated at every step of the food supply chain, such as harvesting, transporting, processing, packaging, and consumption (Dhiman and Mukherjee 2023). Lahiri et al. (2023) highlighted that more than 91 million tons of food waste can be generated per year in China (Alizadeh et al. 2020). Food waste does not merely imply an economic loss, but also generates environmental impacts (Dhiman and Mukherjee 2023). The United Nations via the Environment Programme (UNEP) and partner organization WRAP informed, in the 2021 Food Waste Index Report, that more than 930 million tons of food sold in 2019 landed in waste bins, which represents 17% of the available food in restaurants, households, and shops (UNNews 2021). Therefore, it is imperative to find alternatives to reuse or recycle food waste because it contains carbohydrates, proteins, starch, and lipids (Dhiman and Mukherjee 2023). Nowadays, the common practice in several countries is to dispose of this waste in landfills or to incinerate it with other municipal solid wastes. These practices have consequences, such as the generation and release of harmful environmental pollutants, in addition to the corresponding economic impact.

On the other hand, waste cooking oil (WCO) is generated from catering and food industry and is an important biomass-derived feedstock (e.g., canola, corn, sunflower, safflower oil) to produce biofuels (Li et al. 2023). The generation of this residue reaches 16.54 million tons worldwide annually (Wang et al. 2022a) due to the consumption of 200 million tons of edible vegetable oils (Li et al. 2023). A significant concern is that WCOs are usually disposed in containers or wastewater drains, with the consequent risk of environmental pollution or blockage of sewers and drains (Baghani et al. 2022). The meat and chicken industries are increasing because of the growth of the global human population. Animal fats, including beef tallows, chicken fat, mutton fat, and pork lard, are the most prevalent organic wastes produced globally (Aliana-Nasharuddin et al. 2020). It is estimated that 17 million tons of this type of waste are generated per year in the EU (Sreeharsha et al. 2023), where their inadequate disposal could cause eutrophication and water contamination. However, they are composed of high amounts of fatty acids, which make them a potential feedstock for biodiesel production (Hazrat et al. 2019). The fact that biofuels can be derived from a variety of biomass sources enhances community interest, making them adaptable to diverse regions and contributing to the overall decentralization of energy production (Cheah et al. 2022).

Several estimations indicate that biomass has the capacity to support the global energy system, generating a total of 100 to 400 EJ per year (Vaskalis et al. 2019). Therefore, the selection, valorization, and processing of renewable feedstock are paramount because they represent approximately 80% of the total cost of biofuel production, and waste biomass could considerably reduce these costs (Priya et al. 2022).

The operation of biorefineries has intensified to address the global energy, environmental, and economic issues generated by the consumption of fossil fuels (petroleum products) and to accelerate their substitution with biofuels (Goswami et al. 2022). The implementation of these biomass processing facilities can improve the energy security and environmental conditions of the planet by decreasing greenhouse gas emissions to the atmosphere (Gil 2022), although this is not yet economically feasible for the economic conditions of several countries (Dahlke et al. 2021).

Recent studies indicate that 53 EJ were generated globally in 2018 from renewable energy sources (waste biomass), thus representing approximately 8.7% of the total global primary energy supply where biofuels (solid, liquid, and gaseous) symbolize about ¾ parts of renewable energy (Energy Statistics Pocketbook 2021). Approximately, 160 million liters of biofuels are produced worldwide, with bioethanol and biodiesel accounting for 62 and 26%, respectively, while the remaining 12% is made up of other biofuels (Global Bioenergy Statistics 2020). Note that the 2019 report by the International Energy Agency (IEA) indicates that the energy demand (fuel) is forecasted to increase by 20% by 2050, which has set off alarm bells and prompted the implementation of new renewable sources of green energy, specifically biofuels (International Energy Agency 2021). It is expected that world biofuel demand will increase by approximately 186 billion liters in 2026 compared to previous years (International Energy Agency 2021). Lane (2019) highlighted that each country or region should manage and regulate the evolution of biofuel production and consumption according to its specific economic conditions and characteristics.

Today, the countries that have made significant advances in the supply chain and application of biofuels are the USA, Brazil, China, and the European Union (EU) (Barr et al. 2021). These nations are leading the way in integrating biofuels into their energy matrices, and this development holds great promise for a sustainable energy future. In December 2019, the European Commission presented an ambitious new strategy (the European Green Deal) to support environmental stewardship and, in turn, achieve pollution-free and climate-neutral territory by 2050 (European Commission 2019). This initiative signifies a recognition of the urgent need to combat climate change and transition to cleaner energy sources. By that time, solid and liquid biofuels are expected to represent approximately 60 and 30% of energy matrix, respectively, while the rest would be associated with gaseous biofuels (i.e., biogas) (Piñón-Muñiz et al. 2023).

Techniques and methods used in the production of liquid biofuels

As stated, the economic and sustainable production of biofuels has become a challenge for the scientific community, and it is paramount to improve or find new technologies and strategies to maximize and make profitable the development of this energy source with the aim of reducing its negative impacts on the environment (Boro et al. 2022). It is evident that these challenges require innovative solutions and collaborative efforts to ensure the viability and sustainability of biofuels as renewable energy sources. The production and use of biofuels at the global level mainly depend on the raw materials and production methods, as well as the effectiveness of the entire process (Boro et al. 2022). It has been also pointed out that biomass has become a viable, economic, and promising source to produce sustainable biofuels (Lin and Lu 2021).

Raw biomass as a biofuel shows undesirable characteristics, such as high moisture, hygroscopicity, and heterogeneity, as well as low density and calorific value (Silva et al. 2018). Therefore, the promotion of raw biomass utilization has diminished, and several attractive and competitive processes have been proposed to obtain high-quality fuels derived from thermochemical transformation (Silva et al. 2018). Biofuels derived from biomass can be obtained using various methods (biological, physical, and chemical) (Hajilary et al. 2019). Fermentation, gasification, liquefaction, thermochemical conversion, anaerobic digestion, and transesterification are among the primary biofuel production methods, see Fig. 3.

The thermochemical processes include gasification, liquefaction, combustion, and pyrolysis. Particularly, pyrolysis plays a significant role in the biomass transformation into renewable bioproducts such as bio-oil (Xue et al. 2023), biochar (Zou et al. 2022), and syngas (Dahmen et al. 2019). According to the operating conditions, pyrolytic processes can be categorized into three types: slow, fast, and flash pyrolysis (Rahimi et al. 2022). This differentiation is crucial for optimizing the efficiency and output of the pyrolysis process because each type has its own set of advantages and

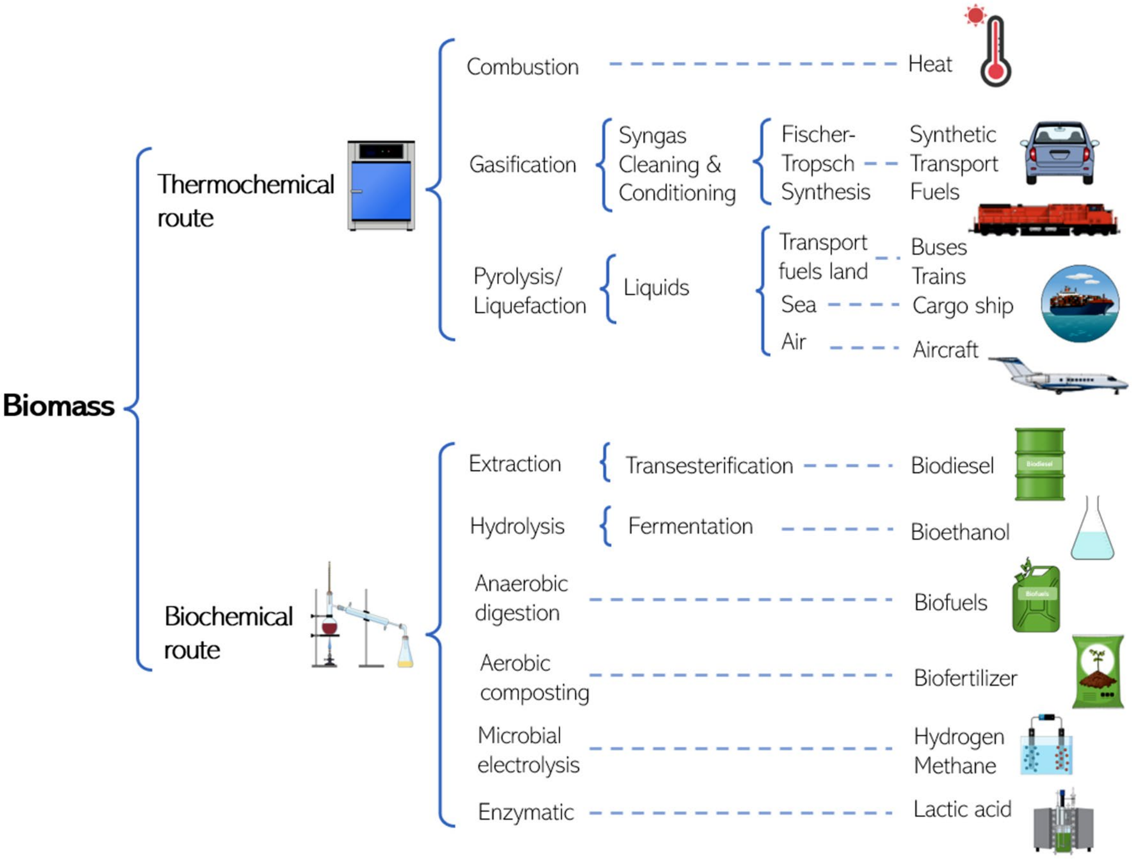


Fig. 3 Thermochemical and biochemical methods for biomass conversion into biofuels

limitations. In addition to the classification of pyrolysis, the choice of technology plays a pivotal role in the generation of biofuels from waste. Various reactor designs have been proposed for producing biofuels from waste via pyrolysis, including fixed beds, rotary kilns, fluidized beds, rotating cones, vacuum reactors, and ablative reactors (Rahimi et al. 2022). The generation of biofuels via waste gasification technologies has mainly focused on fixed beds, fluidized beds, entrained beds, and plasma reactors (Rahimi et al. 2022). These technologies are essential to convert the energy potential of waste materials (Nabi et al. 2022).

It is important to highlight that residual lignocellulosic biomass is a great source of natural sugars derived from biopolymers (e.g., hemicellulose, cellulose, and lignin), which are relevant feedstocks in the operation of biorefineries to obtain a variety of platform chemicals (Patra et al. 2022). The chemical structure of this waste presents a significant challenge for biomass processing and transformation during biofuel production (De Bhowmick et al. 2018). Currently, various lignocellulosic biomass pretreatment methods and technologies (e.g., chemical, physical, physicochemical, and biological approaches) can be combined to achieve this goal, see Fig. 4.

The pretreatment stage plays an important role in the sugar conversion process because it modifies the structure and composition of biomass (Haldar and Purkait 2021). Chemical and enzymatic methods have shown the best performance for the generation of sugars from lignocellulosic biomass (Lu et al. 2022). Although physical and chemical pretreatments have been successful in the production of biofuels, their main limitations are the high consumption of energy and water, the use of specialized equipment and expensive reagents, and the generation of inhibitory compounds that affect biofuel yield and can generate harmful and toxic residues for human health (Ahmed et al. 2022b). Therefore, biological pretreatments are usually suggested because they can operate under moderate reaction conditions (temperature and pressure close to ambient conditions) and are mainly based on the application of microorganisms or enzymes that can alter the structure of lignocellulosic biomass with a low energy demand in an environmentally friendly manner, making them a promising method for the production of biofuels (Ahmed et al. 2022b). Note that the incubation time and efficiency are factors that limit the utilization and selection of biological methods over other pretreatments (Vasco-Correa et al. 2016). This step results in

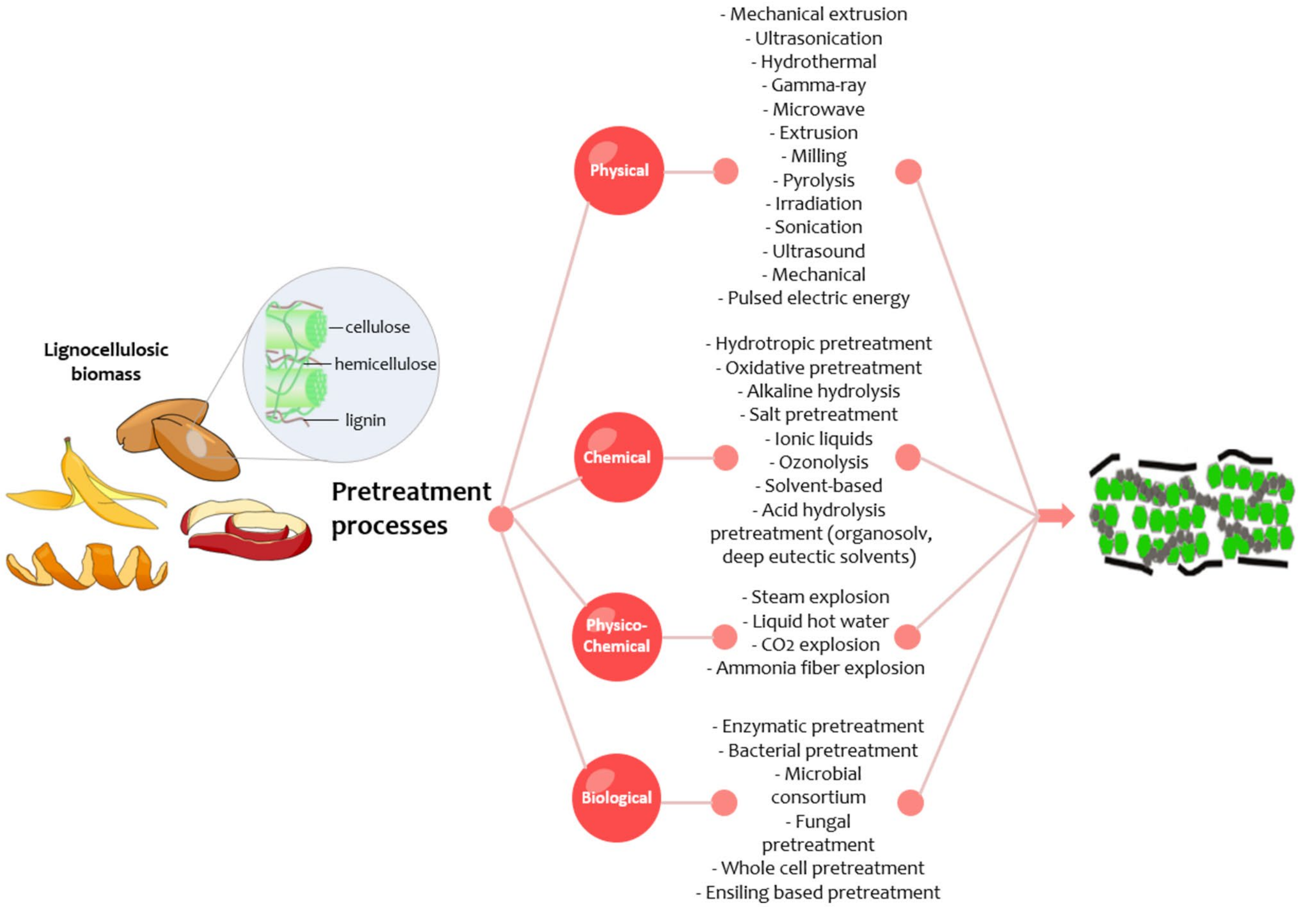


Fig. 4 Summary of methods and technologies used in the pretreatment of lignocellulosic biomass

higher biomass saccharification and generation of bioalcohols (Kumar et al. 2020), which, together with fermentation, are considered the fundamental stages involved in bioalcohol production from lignocellulosic biomass (Cherian et al. 2022).

Biodiesel

Biodiesel has a chemical composition of fatty acid alkyl esters and is a strong candidate to replace conventional petrodiesel in the future. This biofuel can contribute to the global energy crisis because of its multiple benefits, including good performance in combustion engines, low generation of polluting gases (greenhouse gases), non- or low toxicity, biodegradability, and sustainability (Sentanuhady et al. 2022). Biodiesel is generally obtained using four conventional methods: direct blending or dilution, microemulsion, thermal cracking/pyrolysis, and transesterification (Velusamy et al. 2021).

Direct blending or dilution is a cost-effective and simple method in which non-edible oils are directly used as fuels (Vellaiyan 2020) or mixed with petrodiesel, gasoline, ethanol, or other solvents to improve their physicochemical properties (e.g., decrease in viscosity and increase in cetane index and volatility) for an efficient and satisfactory use in combustion engines (Nayab et al. 2022).

On the other hand, microemulsion is an effective and viable method for reducing the viscosity of raw vegetable oils (Nayab et al. 2022). Recent studies have indicated that the use of alcohols (e.g., methanol, ethanol, butanol, and hexanol) can reduce the viscosity of vegetable oils when microemulsions are used (Nayab et al. 2022). Higher-chain alcohols and alkyl nitrates are commonly utilized as surfactants and cetane improvers, respectively (Vellaiyan 2020). This method is energetically profitable and does not require previous treatment of vegetable oils to produce biodiesel with properties comparable to those of traditional diesel (Devarajan et al. 2022).

The pyrolytic processes to transform oils and fats are carried out under an inert atmosphere (absence of oxygen or air) in a temperature range of 350–800 °C, with or without the presence of catalysts. This thermochemical process breaks the chemical bonds of triglyceride chains to obtain biodiesel (Pydimalla et al. 2023). Catalytic pyrolysis has been reported to improve the reaction rate and biodiesel conversion rate, as well as its quality, eliminating oxygenated products and lowering acidity (Ong et al. 2019). Several catalysts, such as zeolites, alumina, sodium and potassium hydroxide, sodium carbonate, and carbon-based catalysts, can be used in the catalytic pyrolysis (Abdelfattah et al. 2018). Currently, fluidized bed reactors (e.g., bubbling and circulating) (Mullen and Boateng 2019), concentrated solar rotating reactors (Niyas and Shaija 2023), and microwave (Anis et al. 2021) have been proposed for biodiesel production. The yield and properties of biofuels are strongly related to parameters such as feedstock, reactor design, heating rate, pyrolysis temperature, residence time, and catalyst type (Abdelfattah et al. 2018). Biodiesel obtained using this method shows improved physicochemical properties such as a high cetane index, low sulfur content, and viscosity (Pydimalla et al. 2023). However, the biodiesel obtained from this route must be neutralized and pretreated because of its high moisture content and low density (Johansson et al. 2021).

Transesterification (alcoholysis) is the most common method for producing biodiesel and consists of a reaction between triglycerides (lipid source) and an alcohol, preferably short chain (methanol and ethanol), in the presence of a catalyst (homogeneous, heterogeneous, or biocatalyst) (Pydimalla et al. 2023). Generally, the variables that have the greatest impact on the profitability of the transesterification process are the catalyst (type, loading, and concentration), alcohol-to-oil molar ratio, temperature, stirring, and reaction time (Günay et al. 2019). It is worth noting that the (reversible) transesterification reaction requires a stoichiometric alcohol-to-oil molar ratio of at least 3/1 to complete the chemical reaction and favors the production of biodiesel and glycerol (a valuable by-product) (Günay et al. 2019). In general, excess alcohol is required to shift the reaction forward, thus favoring the formation of products (Ahmed et al. 2023). Catalytic transesterification is currently one of the preferred and most widely used methods because of its simplicity and the fact that a wide variety of lipid sources and catalysts can be employed, thus offering high conversion and biodiesel yields under moderate reaction conditions (Nayab et al. 2022; Shahbeik et al. 2022; Pandit et al. 2023). Novel and innovative synthesis methods have been proposed to obtain biodiesel, including transesterification using microwave technology, in situ transesterification, ultrasound-assisted transesterification, transesterification using membrane technology, reactive distillation, and supercritical fluid technology (non-catalytic method) (Quah et al. 2019).

Renewable diesel

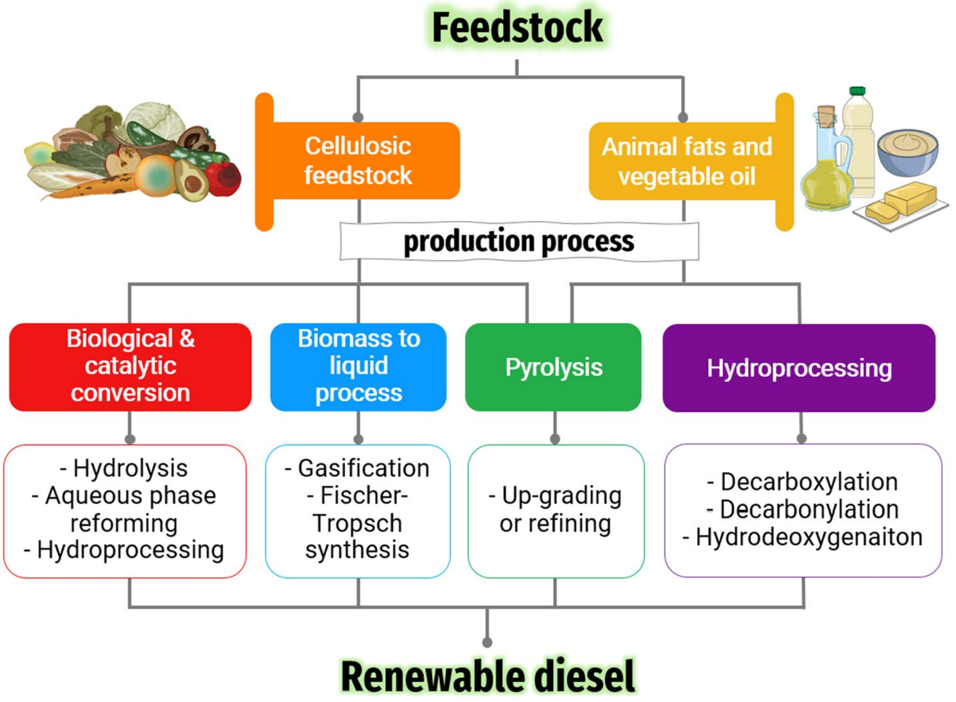
Renewable diesel is also known as green diesel (Knothe 2010), hydrotreated vegetable oil (HVO) (Douvartzides et al. 2019), or 2G diesel (Julio et al. 2022). This renewable fuel is a mixture of saturated straight-chain and branched hydrocarbons (C_{15}–C_{18}) (Douvartzides et al. 2019), mainly composed of paraffins with properties comparable to those of petrodiesel. Some attractive properties of this biofuel are its high cetane content and calorific value, low oxygen content, excellent storage stability, non-corrosiveness, and high energy density (Chia et al. 2022). Therefore, this biofuel can be used as an additive or directly as fuel in diesel engines, showing excellent performance and a decrease in the emission of polluting gases (CO_2) into the atmosphere compared to traditional diesel (Knothe 2010). Lipid-rich feedstocks (i.e., oils, animal fats, and lignocellulosic biomass) are generally used to produce renewable diesel (Douvartzides et al. 2019). Depending on the type of feedstock used, different synthesis routes and technologies can be utilized to produce renewable diesel, see Fig. 5. Renewable diesel from lignocellulosic biomass, starches, carbohydrates, and sugars can be obtained via biological and catalytic conversion, gasification, Fischer–Tropsch (biomass to liquid process), and pyrolysis, whereas lipid sources (triglycerides) are mainly treated by thermochemical processes (pyrolysis) and hydroprocessing/hydrotreatment (Chia et al. 2022). These biomass conversion processes require advanced and efficient technologies to achieve the highest quality and yield of products with the lowest cost and environmental impact (Chia et al. 2022).

Bioalcohols

Bioalcohols (bioethanol, biopropanol, and biobutanol) have increased in popularity worldwide and are considered green and renewable alternative sources of energy (Ambaye et al. 2021). They can also be obtained from various biomass sources (Huzir et al. 2018). This is particularly important for diversifying the energy resources and reducing the reliance on a single feedstock type (Renewables 2020). Different studies have improved and developed new techniques to produce bioalcohols with the aim of achieving properties comparable to those of gasoline (i.e., flammability, thermal efficiency, high evaporation enthalpy, and octane rating) (Singh et al. 2020). Bioalcohol production from biomass involves a series of stages such as pretreatment, enzymatic hydrolysis, saccharification, fermentation, and purification (e.g., distillation), see Fig. 6.

Bioconversion of lignocellulosic biomass from modified microorganisms (metabolically and genetically) has become an excellent option for increasing the production of bioalcohols (Lu et al. 2022). Recent studies have indicated that microbes belonging to the actinobacteria can generate a wide variety of efficient enzymes used in the decomposition and degradation of biomass (Lu et al. 2022). The ability to use these enzymes to break down lignocellulosic materials is a significant step toward making the bioalcohol production

Fig. 5 Synthesis routes and technologies used to produce renewable diesel from biomass



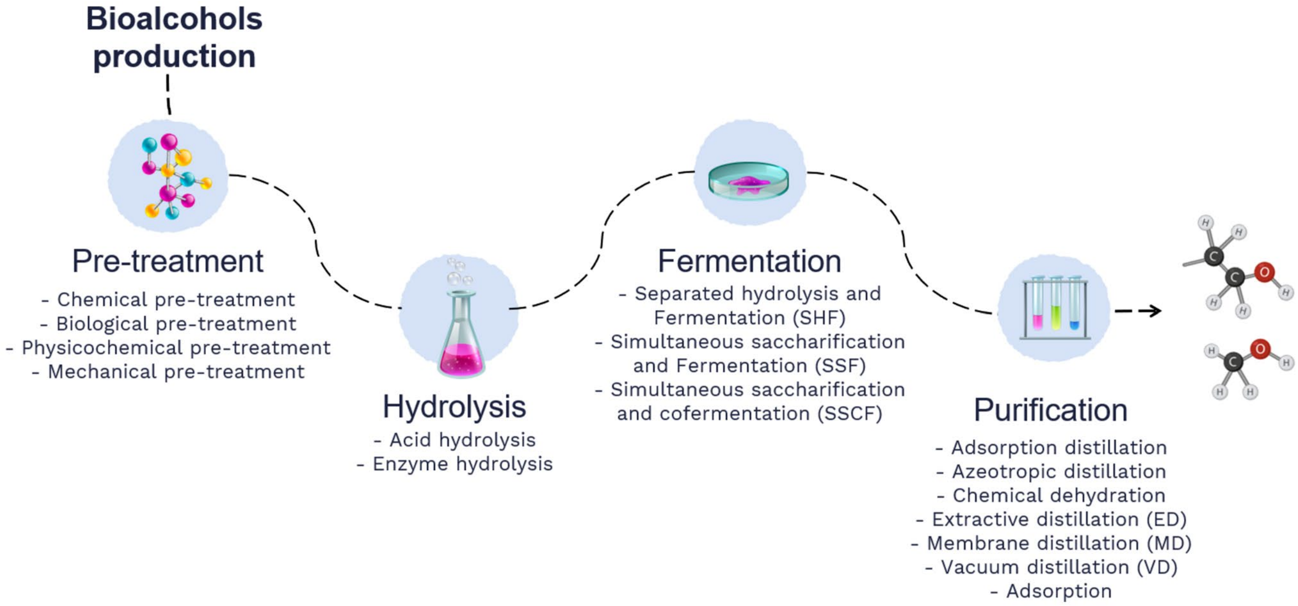


Fig. 6 Methods and technologies involved in the production of bioalcohols from biomass

more efficient and cost-effective. This is also evidence of the versatility of nature and value of microbial diversity in sustainable bioprocesses. For example, hydrolytic enzymes can easily obtain sugars. Several researchers have reported that biomass pretreatment plays a fundamental role in achieving high amounts of simple sugars for subsequent fermentation (Avinash et al. 2020). Saccharification reactions (Cherian et al. 2022) and fermentation (Luo et al. 2020) are considered to have the greatest impact on bioalcohol conversion from lignocellulosic biomass.

Microbes are important in the fermentation process and are used to obtain value-added chemicals, combustion gases, and biofuels (bioalcohols) via the biological transformation of lignocellulosic biomass (Luo et al. 2020). Note that ethanol and butanol are usually produced by the fermentation of a wide variety of biomass sources based mainly on the traditional industrial process known as acetone-butanol-ethanol (ABE) fermentation (Carmona-García et al. 2021). On the other hand, nanocatalysts have been used to improve bioalcohols production in the synthesis gas (syngas) fermentation (Avinash et al. 2020). Specifically, a wide group of metallic nanoparticles, such as ruthenium and nickel (Cimino et al. 2018), palladium over Mg–Al oxides (Quesada et al. 2018), copper (Siqueira et al. 2019), zinc (Gu et al. 2022) among others, has been used as effective catalysts for their production. Cherian et al. (2022) proved that nanocatalysts derived from zeolites, hydroxyapatite, and hydrotalcites can exhibit high catalytic activity and selectivity in the conversion of ethanol to butanol. In addition, CuZnAlOOH catalysts have been utilized in a two-step hydrolysis to produce ethanol from syngas (Gu et al. 2022).

Bio-oil

In recent years, bio-oil has attracted attention as a novel renewable biofuel because of its biodegradability and environmental friendliness. Another advantage of this biofuel is its high energy density, ease of storage, and performance during its utilization in combustion engines, which reduces the levels of polluting gases (CO_2, NO_x, and SO_x) released into the atmosphere (Zhang et al. 2020b). Currently, thermochemical techniques (pyrolysis and liquefaction) are the most used to produce bio-oil from biomass, see Fig. 7. Other technologies such as hydrolysis/solvolysis can be employed (Biswas et al. 2021). The pyrolytic (400–600 °C) and liquefaction (250–400 °C) processes have different operating temperature conditions (Velusamy et al. 2021). Note that bio-oils are characterized by a complex composition with a wide molecular weight, highly oxygenated compounds, and low pH values (2–3). Therefore, the complete deoxygenation of the bio-oil is required to improve its properties such as viscosity and oxidative stability (Nogales-Delgado et al. 2020) and, caloric value and acidity (Li et al. 2021). It is convenient to point out that the properties of bio-oil can be improved via the use of chemical / physical (Bridgwater 2018) and catalytic methods (Mardiana et al. 2022). For example, Bridgwater (2018) achieved physical improvements in pyrolytic bio-oil obtained from filtration, emulsion, and solvent addition processes. Various researchers have opted for novel catalytic methods, such as hydrodeoxygenation and zeolite cracking, to improve and overcome these limitations in terms of oxygenation and stability (Mardiana et al. 2022). The hydrodeoxygenation process requires the presence of catalysts (i.e., CoMo, NiMo, Ru, Pd, and Pt) for the total deoxygenation of the bio-oil and oxygen elimination in the form of water. The main factors that affect the properties and performance of bio-oil during this process are the residence time, temperature, type of solvent, type of catalyst, and hydrogen pressure (Zhang et al. 2021).

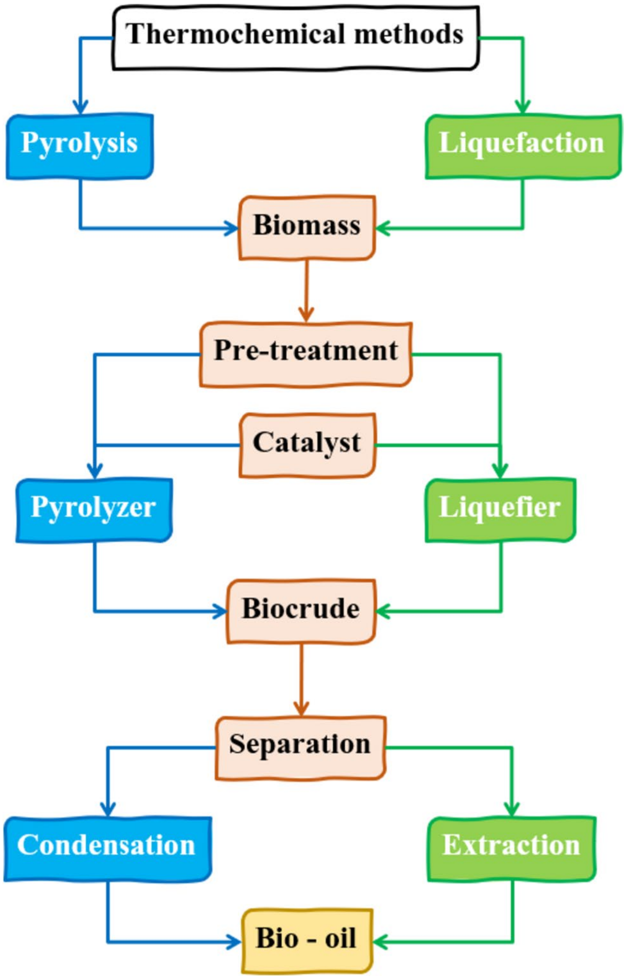


Fig. 7 Thermochemical methods for biomass transformation to bio-oil

Bio-jet

Traditionally, the kerosene produced from crude oil has been used to produce aviation fuel. Approximately, 300 million tons of aviation fuel are consumed every year globally, and this demand will double by 2050 (Hussain et al. 2022). It is concerning that the aviation industry contributes 2.5% of global CO_2 emissions (Ravindran et al. 2022). Therefore, the transition to bio-jet in the aviation industry is not just a desirable move but a necessary one (Skrotskyi et al. 2019). As air travel has become increasingly vital in a globalized world, it is imperative to address the sector's carbon footprint and its contribution to climate change. The fact that aviation is responsible for a significant share of global CO_2 emissions highlights the urgency to find sustainable alternatives for the energy supply of this sector. Bio-jet, often known as aviation turbine fuel, can be used as a replacement for conventional kerosene in the aviation industry (Wei et al. 2019). The typical composition of a bio-jet consists of hydrocarbons (C_8–C_{16}), such as alkanes, iso-alkanes, naphthenic or naphthenic derivatives, and aromatic compounds (Wei et al. 2019). Biochemical and thermochemical routes have been developed to produce this biofuel, see Fig. 8. The first pathway involves the use of enzymes or microorganisms, whereas the second pathway utilizes processes such as syngas derived from pyrolysis or gasification technologies (Wei et al. 2019). The catalytic hydrodeoxygenation of biomass-derived oil and the Fischer–Tropsch synthesis of biomass-derived syngas are common technologies to obtain bio-jet (Wei et al. 2019).

Hydrodeoxygenation and hydro-thermolysis methods consist of a series of reactions, such as catalytic hydrogenation, hydrodeoxygenation, carboxylation, cyclization, cross-linking, cracking, hydrolysis, and isomerization, which allow obtaining high-energy biofuels with suitable properties such as thermal stability, high cetane number, and low tailpipe emissions, but with low aromatic content (Wei et al. 2019).

The Fischer–Tropsch (FT) process converts syngas into transportation fuels with high specific energy and no sulfur emissions (Liu et al. 2013). This process involves six steps: feedstock pretreatment, biomass gasification, gas conditioning, acid gas removal, FT synthesis, and syncrude refining (Wei et al. 2019). The selectivity of the catalyst is fundamental for obtaining target hydrocarbons. However, these technologies involve multiple steps and complex procedures. Continuous efforts to develop optimal processes are being undertaken to obtain more economical and sustainable technologies, where catalytic co-pyrolysis stands out as a simple and effective alternative to obtain high-quality biofuels (Wei et al. 2019).

Recent advances on the thermochemical transformation of biomass into biofuels

It is clear that various types of biomass have been used as raw materials to produce bioenergy (electricity) and biofuels (biochar, syngas, biohydrogen, bio-oil, biogas, biodiesel, and bioethanol) using different methods and conversion techniques (Lee et al. 2019). The most relevant biomass sources for biofuel production include wood, agricultural residues, oil sources (used cooking oils), and aquatic biomass (microalgae) (Lee et al. 2019). In the following sections, recent studies on biofuel production and their results are discussed (Wang et al. 2020).

Biodiesel

As discussed in Sect. "Biodiesel", biodiesel is one of the most widely studied biofuels as an alternative to petroleum derivatives. Commercial biodiesel is produced from edible oils. However, this is not a sustainable long-term solution. To offer a long-term option, the selection of biomass feedstock to obtain oil that will be converted into biodiesel is fundamental. Therefore, diverse and attractive biomass wastes have been proposed for its production. Table 1 shows recent studies that have focused on the feasibility and valorization of alternative biomass-derived oils to produce biodiesel.

Shen et al. (2018) evaluated the performance of *Xanthoceras sorbifolia* Bunge seed kernel oil as a raw material for biodiesel production. This biomass has a high lipid content and composition like that of conventional diesel, which makes it an imminent and promising raw material for biodiesel production. The seeds were dried at 80 °C and ground to carry out oil extraction via the Soxhlet method using petroleum ether as the solvent at 120 °C for 5 min, leaching for 1 h, and a subsequent recovery for 25 min. Transesterification was performed using 0.06 g of oil, 4 mL

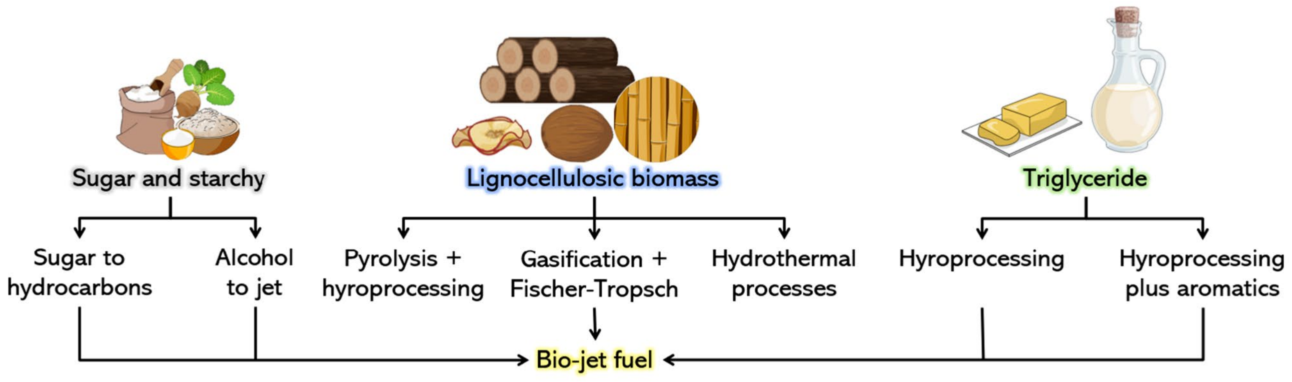


Fig. 8 Conversion methods used to produce bio-jet from biomass

Table 1 Recent studies of use of biomass waste as potential feedstock to produce biodiesel

Waste	Catalyst	Biomass treatment conditions	Reaction conditions	Yield or conversion, %	References
Transesterification					
Waste sewage sludge	Ni/HZSM-5	Fast pyrolysis: 500 °C, particle size: 0.6 mm, vapor residence time: 1.95 s	259 °C, 3.23 h, ethanol/oil ratio: 2.5:1, 1.2 g of nickel-modified HZSM-5	67	Arazo et al. (2017)
Passion fruit	H_2SO_4	Soxhlet extraction (seeds): solvent (hexane), 4 h, the O/solvent mixture was treated with $MgSO_4$ (2 h) to remove water	70 °C, 2 h, methanol/oil molar ratio: 7/1, H_2SO_4/O molar ratio: 0.09	99	Iha et al. (2018)
Guava fruit				99	
Castor oil	KOH	--	60 °C, 30 min, 1 wt% of KOH, methanol/oil ratio: 9/1	95	Keera et al. (2018)
Xanthoceras sorbifolia Bunge seed kernel oil		Soxhlet extraction: petroleum ether, 120 °C, 5 min, leaching for 1 h, recovery for 25 min	0.06 g of oil, 4 mL isooctane, 0.2 mL KOH–methanol (2 mol/L), 30 s	100	Shen et al. (2018)
Pongamia pinnata raw oil	Fe_3O_4 nanoparticles impregnated eggshell (CES-Fe_3O_4)	—	65 °C, 2 h, methanol/oil ratio: 12/1, 2% of CES-Fe_3O_4	98	Chingakham et al. (2019)
Pig fat and neem (*Azadirachta indica* a.Juss) seeds	CaO	2 kg of pig fat washed with disodium carbonate and disodium sulfate. Neem oil removal by heating, 30 °C, 20 min	60 °C, 58 min, 2.179 g of CaO, methanol/neem oil-pig fat (60/40): 5.9/1	98	Adepoju (2020)
Corn oil	SrO-ZnO/Al_2O_3 bifunctional	–	70 °C, 3 h, ethanol/oil ratio: 10/1, 10% of SrO–ZnO/Al_2O_3 bifunctional	95	Al-Saadi et al. (2020)
Jupati (*Raphia taedigera* Mart.) oil	Murumuru kernel shell biochar sulfonated	–	135 °C, 4 h, methanol/oil ratio: 30/1, 6% of Murumuru kernel shell biochar sulfonated	92	Bastos et al. (2020)
Waste cotton-seed cooking oil	KOH and CaO	–	KOH: methanol/oil ratio: 6.1/1, 53 °C, 0.46%	KOH: 98	Sharma et al. (2020)
			CaO: methanol/oil ratio: 10.9/1, 48 °C, 0.96%	CaO: 96	
Terminalia chebula oil	CuO	Soxhlet and mechanical extraction (seeds): 50 g of biomass, n-hexane: 300 mL, 15 h	60 °C, 1 h, methanol/oil ratio: 9/1, 3% of CuO, 650 rpm	97	Yatish et al. (2021)
		Soxhlet extraction (leaves): 50 g of biomass, 72 h, the water-extract was dried (80 °C, 3 h)			
Waste sewage sludge	NaOH	Soxhlet extraction: sewage sludge to MeOH ratio: 1/10, 70 °C, 8 h	60 °C, 4 h, methanol/oil ratio: 9/1, 5% of NaOH	84	Alsaedi et al. (2022)

Table 1 (continued)

Waste	Catalyst	Biomass treatment conditions	Reaction conditions	Yield or conversion, %	References
Wild mustard *(Sinapis Arvensis)* seed oil	$LaTiO_3$	–	80 °C, 1 h, methanol/oil ratio: 4/1, 5% (100 mg) of $LaTiO_3$	92	Rezania et al. (2022)
Citrus medica seed oil	CuO nanoparticles	Soxhlet extraction: 5 g of biomass, n-hexane: 250 mL, 60 °C, 5 h	85 °C, 2 h, methanol/oil ratio: 8/1, 0.18% of CuO nanoparticles	93	Rozina et al. (2022)
Waste cooking oil	Banana pseudostem based-ash	–	60 °C, 2 h, methanol/oil ratio: 9.35/1, 4.7% of banana pseudostem based-ash	98	Daimary et al. (2023)
Jojoba *(Simmondsia chinensis)* seed oil	KOH	Mechanical extraction: solvent (n-hexane)/B ratio: 14.6 cc/1 g, 64.5 °C, 187.7 min, 93.2 rpm	50 °C, 2.25 h, methanol/oil ratio: 5.5/1, 0.475% of KOH	67	Safaripour et al. (2023)
Cannabis sativa seed oil	Bi_2O_3 nano-catalyst	Soxhlet extraction: 5 g of biomass, n-hexane: 230 mL, 60 °C, 5–6 h	92 °C, 3.5 h, 1.5 wt.% of Bi_2O_3 nano-catalyst, methanol/oil ratio: 12/1, membrane reactor	92	Sawaira et al. (2023)
Pyrolysis					
Castor raw oil	NaOH and ZMS-5 combined with NaOH	Catalytic pyrolysis	233–347 °C, 200–310 min, 1 wt% NaOH, 1 L of oil	92	Abdelfattah et al. (2018)
Waste clay oil	Cu/activated carbon	Catalytic pyrolysis	550 °C, 0.2 L/min N_2, 10 g of oil, 15% of Cu/activated carbon	91	Yuan et al. (2021)
Supercritical fluids					
Waste sewage sludge	-	Drying at 105 °C for 2 days Soxhlet extraction with hexane	100 °C, 5 h, methanol/oil ratio: 10/1,7% of ionic liquid	90	Olkiewicz et al. (2016)
Calophyllum inophyllum oil	–	Cold pressing of seeds	349.85–399.85 °C, 0.5 h, 30 MPa, methanol/oil ratio: 40/1, Methyl tert-butyl ether, Methyl acetate, Dimethyl carbonate	Methanol and dimethyl carbonate: > 80 Methyl acetate: 60 Methyl tert-butyl ether: 70	Lamba et al. (2017)
Pig fat	–	–	290 °C, methanol/oil ratio: 67.5/1	99	Poudel et al. (2017)
Schizochytrium limacinum microalgae	–	Lyophilized powder	269.85 °C, 40 min, 20 MPa, methanol/oil ratio (v/wt): 10/1	> 90	Rathnam and Madras (2019)
Schizochytrium limacinum microalgae	–	–	319.85 °C, 50 min	Ethanol: > 95	Rathnam et al. (2020)
			379.85 °C, 50 min, 20 MPa, ratio of algae to ethylating agent (wt./v): 1/10	Ethyl acetate: > 60	
Rapeseed oil	–	–	850 °C, 0.5 h, 20 MPa, water/methyl acetate ratio: 2 wt% (8.3 mol%)	97.95	Ridwan et al. (2020)

Table 1 (continued)

Waste	Catalyst	Biomass treatment conditions	Reaction conditions	Yield or conversion, %	References
Leather tanning waste	–	–	375 °C, 47 min, 15 MPa, ethanol/oil ratio: 40/1	98.9	Yuliana et al. (2020)
Spent coffee grounds	–	Soxhlet extraction with ethyl acetate and n-hexane	325 °C, 50 min, 15 MPa, ethyl acetate/oil ratio: 30/1	91.8	Supang et al. (2022)

Ethanol, methanol

of isooctane, 0.2 mL of KOH–methanol (2 mol/L), and this system reached a biodiesel conversion of 99.77%.

Abdelfattah et al. (2018) focused on the production of biodiesel from the pyrolysis of raw castor oil employing different types of catalysts. A biodiesel yield of 91.7% was obtained from oil catalytic pyrolysis, which was carried out under the following reaction conditions: 1 L of oil, 233–347 °C, 200–310 min and 1 wt% NaOH.

The use of supercritical fluids to produce biodiesel is an interesting alternative because methanol (or other alcohols) acts as a medium and reactant without the need for a catalyst, thus causing that the catalyst separation is not needed, and the reaction time is shorter than that of the catalytic reaction (Lee et al. 2021). The advantages of this approach were demonstrated by Lamba et al. (2017). They tested *Calophyllum inophyllum* oil as a lipid feedstock for biodiesel production using dimethyl carbonate (DC), methyl acetate (MA), methyl tert-butyl ether (MTBE) and methanol (Met). Biodiesel production under non-catalytic supercritical conditions was performed by varying the temperature (250–400 °C) and time (3–180 min) under a constant pressure of 30 MPa and a reagent/oil molar ratio of 40/1. The highest biodiesel conversions ($^{>}$ 80%) were obtained at 30 min in the presence of the solvents DC and Met at 350 °C, while with MA and MTBE at 400 °C achieved conversions of 60 and 70%, respectively (Zhang et al. 2016).

Trentini et al. (2019) tested the transesterification of grease trap waste under supercritical conditions. The effects of different water concentrations (in ethanol) on the production of ethyl esters were also evaluated. The reactions were carried out in a continuous reactor at several temperatures (275, 300, and 325 °C) and residence times (10, 20, and 30 min) using ethanol with water at various concentrations (2.5 to 10 wt%) at 20 MPa. Ester production improved with the use of water at low residence times. The highest ester yield (92.6%) and lowest content of unreacted compounds (5.5 wt%) were obtained using ethanol with 2.5 wt% of water.

Soy sauce residue (SSR) is a by-product of soy sauce production, where 450,000 tons/year of this waste is generated globally (Xiang et al. 2019). This biomass contains up to 36% oil and can be used to produce biodiesel. Xiang et al. (2019) produced biodiesel from SSR using a novel process based on supercritical CO_2 and evaluated the influence of parameters such as the size of the raw material, reaction pressure, temperature, time, and methanol/oil molar ratio. It is noteworthy that the oil showed a high free fatty acid content (71 mg KOH/g), which negatively impacted the traditional alkaline transesterification. However, its effect was negligible in supercritical systems. The optimal conditions were a particle size of 60 mesh, 16 MPa, 100 °C, 180 min, and a methanol-to-oil molar ratio of 35:1. This system resulted in a biodiesel yield of 96%.

Two types of residual biomass (neem oil seed and pig fat) from different origins were used as lipidic feedstock in catalytic transesterification by Adepoju (2020). Disodium carbonate was used to wash pork fat under continuous stirring for 25 min. Two phases were formed, and centrifugation was used for separation. The mixture with a ratio (v/v) of neem oil/pig fat of 60/40 presented low viscosity (1.50 mm^2/s) and high fatty acid content. Hence, a previous esterification of the oil mixture was necessary. The catalytic transesterification of the mixture of esterified oils was carried out at 60 °C for 57 min, with a methanol/neem oil-pig fat ratio of 5.9/1, and 2 g of catalyst (CaO). The system achieved a biodiesel yield of 98%.

Sewage sludge has become an important biomass that is widely used as a raw material for the production of biodiesel (Arazo et al. 2017; Alsaedi et al. 2022). The global sewage sludge production is calculated in 12.9 Mt, and its disposal accounts for 30–50% of the total cost of wastewater treatment plant operation (Capodaglio and Callegari 2018). Therefore, it is a valuable source of raw lipids. Arazo et al. (2017) used this biomass (0.6 mm particle size) for pyrolytic treatments as a bio-oil production method. The pyrolysis process was carried out at 500 °C for 1.95 s in a fluidized bed reactor. Once the process was completed, the bio-oil was used as a lipid feedstock to obtain biodiesel via catalytic transesterification. A biodiesel yield of 67.2% was achieved under the following optimal reaction conditions: 258.5 °C, 3.23 h, ethanol-to-bio-oil mass ratio of 2.50, and catalyst loading of 1.2 g of nickel-modified HZSM-5. The obtained biofuel sample was of high quality with a caloric power of 29.97 MJ/kg. In another study, Alsaedi et al. (2022) analyzed the utilization of municipal sewage sludge as an alternative energy source for biodiesel production using methanol as a solvent for lipid extraction via the Soxhlet method. The optimal extraction conditions were 70 °C for 8 h and a sewage sludge/methanol ratio of 1/10, obtaining a maximum lipid recovery of 27%. Biodiesel production was carried out via catalytic transesterification at 60 °C for 4 h with a methanol-to-oil ratio of 9/1 and 5 wt% catalyst, with a biofuel yield of 84%. This biodiesel complied with ASTM specifications and the quality requirements established worldwide.

Renewable diesel

The production of diesel from renewable sources is a promising approach in the biofuel industry. The biomass used to produce biodiesel can also be utilized to generate renewable diesel. Several types of biomass sources rich in triglycerides (edible/non-edible oil, vegetable oils, natural fats, animal fats, greases, waste cooking oil, and lignocellulosic material) can be used as raw materials to produce green biofuels (Douvartzides et al. 2019). As indicated, the production route and methods of renewable diesel vary depending on the type of starting raw material (Chia et al. 2022). Recent statistics indicate that in 2020, the USA stood out with a production of 533 million gallons of green diesel, and greater production of this biofuel (2.65 billion gallons) is expected for 2024 (Kelly 2021). Table 2 shows the potential of biomass as a raw material for obtaining renewable diesel.

The catalytic treatment of residual chicken fat has been of interest to the scientific community, as this waste is considered a suitable raw material for producing renewable diesel because approximately 10.7–12.9 million metric tons are generated per year (Aliana-Nasharuddin et al. 2020). Hanafi et al. (2016) used residual chicken fat as a low-cost feedstock to obtain renewable diesel via catalytic hydrocracking. The implementation of this technique enables the production of biofuels with physicochemical properties comparable to those of conventional diesel or other types of fuels derived from petroleum. This renewable diesel production process was implemented in a continuous reactor at 400 °C, 6 MPa, 150 mL/min H_2, 450 v/v (H_2/oil ratio), and LHSV of 4 h^{-1} with a maximum conversion of 94.2%. The results showed that the catalyst maintained good stability and could be used for several reaction cycles, thus efficiently producing naphtha with limited performance for the generation of long-chain alkanes.

Overall, it has been established that the cost of deoxygenation is lower than hydrodeoxygenation. This process has been explored by Aliana-Nasharuddin et al. (2020) to obtain green diesel via the catalytic deoxygenation of chicken fat oil using binary metal pairs (Ni–Mg, Ni–Mn, Ni–Cu, Ni–Ce) loaded on multi-walled carbon nanotubes (MWCNTs) as catalysts. A semi-batch reactor was used to determine the catalytic activity and effect of the catalysts in the deoxygenation reaction carried out at 350 °C for 2 h with 50 mL/min N_2 and 3 wt% catalyst. Specifically, the catalyst with 10 wt% Ni and 15 wt% Mg in the support (Ni_{10}-Mg_{15}/MWCNT) showed the highest stability and catalytic activity, achieving 90% conversion, where the green diesel satisfied the quality standards in terms of sulfur content and heating power.

Scaldaferri and Pasa (2019a) reported the production of liquid biofuels, such as renewable diesel, from upgrading reactions (deoxygenation, hydrogenation, and cracking) of cashew nutshell liquid (CNSL) in the presence of Pd/C catalysts under different conditions. This biomass is produced from *Anacardium occidentale*, a non-food product and industrial waste that can be used as a renewable raw material to obtain renewable diesel. Note that this biomass is easy to cultivate. The catalytic activity of palladium supported on activated carbon (Pd/AC) was evaluated. Catalyst tests were carried out in a batch reactor obtaining a maximum conversion yield of 98% under the following optimal reaction conditions: 10% w/w Pd/C, 300 °C, 10 h, 4 MPa, and 500 rpm. The production of renewable diesel derived from CNSL can be implemented on an industrial scale (biorefinery), offering

Table 2 Recent studies of use of biomass waste as potential feedstock to produce renewable diesel

Waste	Catalyst	Process/reaction	Reaction conditions	Yield or conversion, %	References
Jatropha oil	Fe/activated carbon	Hydroprocessing	360 °C, 3 MPa, liquid hourly space velocity of 0.8 h^{-1}	99	Liu et al. (2015)
Soybean oil	Ni_2P/silica	Hydroprocessing	330 °C, 3 MPa, 300 mL/min H_2, liquid hourly space velocity of 3 h^{-1}	NA	Zarchin et al. (2015)
Chicken fats	$NiW/SiO_2–Al_2O_3$	Hydrocracking	Continuous reactor, 400 °C, 6 MPa, 150 mL/min H_2, H_2/O ratio: 450 v/v, Liquid hourly space velocity of 4 h^{-1}	94	Hanafi et al. (2016)
Rubber seed oil	Pd/activated carbon	Decarboxylation	375 °C, 4 MPa	90	Cheah et al. (2017)
Sunflower oil	$Ni–Al_2O_3$	Selective deoxygenation	310 °C, 9 h, 4Mpa H_2, O (mL)/catalysts (g) ratio: 100/1	˃ 95	Gousi et al. (2017)
Kernel oil (*Phoenix dactylifera*)	Pd/activated carbon	Hydrodeoxygenation	300 °C, 5 h, 1 MPa, 500 rpm	72	Jamil et al. (2017)
Rubber seed oil	Pd	Hydrotreatment	310 °C, 5 h, 2 MPa H_2, oil (mL)/catalyst (g) ratio: 15	100	Yubao et al. (2017)
Waste oils (waste vegetable oil, Waste cooking oil)	$NiMo–Al_2O_3$	Deoxygenation	Semi-batch reactor, 310 °C, 9 h, 4 MPa H_2, reactant (mL)/catalysts (g) ratio: 100/1	˃ 95	Kordouli et al. (2018)
Waste oils (Waste vegetable oil, Waste cooking oil)	$Ag_2O_3–La_2O_3$/activated carbon	Deoxygenation	350 °C, 2 h, N_2, 1% of catalyst	NA	Abdulkareem-Alsultan et al. (2019)
Waste oils (Waste vegetable oil, Waste cooking oil)	Ni supported on palygorskite	Hydrotreatment	Semi-batch reactor, 310 °C, 9 h, 4 MPa H_2, reactant (mL)/catalysts (g) ratio: 100/1	~ 100	Lycourghiotis et al. (2019)
Cashew nutshell liquid	Pd/activated carbon	Hydroprocessing	Batch Reactor, 300 °C, 10 h, 4 MPa H_2, 500 rpm	98.00	Scaldaferri and Pasa (2019a)
Soybean oil	Pd/activated carbon	Deoxygenation	350 °C, 5 h, 1 MPa H_2, 25% of catalyst, 500 rpm	NA	Scaldaferri and Pasa (2019b)
Karanja oil (Pongamia)	$NiMo/Mn–Al_2O_3$	Hydrodeoxygenation	340 °C, 4 h, 3 MPa H_2	100	Yenumala et al. (2019)
Chicken fats	$Ni_{10}–Mg_{10}$ /multi-walled carbon nanotubes and $Ni_{10}–Mn_{10}$ /multi-walled carbon nanotubes	Deoxygenation	Semi-batch reactor, 350 °C, 2 h, 50 mL/min N_2, 3% of catalyst	90	Aliana-Nasharuddin et al. (2020)
Palm fatty acid distillate	$Co_{10}Mo_{10}$/activated carbon	Deoxygenation	350 °C, 2 h, 50 mL/min N_2, 400 rpm, 3% of catalyst	NA	Gamal et al. (2020)
Sunflower oil	Ni_2Cu-Alumina	Selective deoxygenation	310 °C, 4 MPa, 96 mL/min H_2, reactant (mL)/catalysts (g) ratio: 100/1	˃ 95	Gousi et al. (2020)
Cashew nutshell liquid	Co/zeolite mordenite	Hydrotreating	Semi-batch reactor, 450 °C, 2 h, 20 mL/min H_2, 2% of catalyst	98	Hapsari et al. (2020)
Palm fatty acid distillate	Ni/SBA-15 and Ni–Co/SBA-15	Deoxygenation	Semi-batch reactor, 350 °C, 3 h, 10% of catalyst	86—88	Kamaruzaman et al. (2020)

Table 2 (continued)

Waste	Catalyst	Process/reaction	Reaction conditions	Yield or conversion, %	References
Macuba oil	Co/activated carbon	Deoxygenation	Batch reactor, 350 °C, 2 h, 3 MPa H_2, 10 wt% of catalyst, 300 rpm	97	Moreira et al. (2020)
Cashew nutshell liquid	Ni/zeolite mordenite	Hydrotreating	Semi-batch Reactor, 450 °C, 2 h, 20 mL/min H_2, 2% of catalyst	98	Permata and Trisunaryanti (2020)
Palm oil	Ni/ZrO_2	Deoxygenation	350 °C, 3 MPa, H_2/O ratio: 1000, 0.1 mL/min	˃ 95	Hafeez et al. (2021)
Sunflower oil	$Ni\text{-}Al_2O_3$	Selective deoxygenation	Semi-batch Reactor, 310 °C, 9 h, 4 MPa, 100 mL/min H_2, reactant (mL)/catalyst (g) ratio: 100/1	˃ 99	Papadopoulos et al. (2021)
Palm oil	NiP, Co_2P and Cu_3P	Hydrodeoxygenation	350 °C, 6 h, 5 MPa H_2, 109 mL/min H_2, Liquid hourly space velocity of 1 h^{-1}	100	Ruangudomsakul et al. (2021)
Waste oils (Waste vegetable oil, Waste cooking oil)	$NiMo/Al_2O_3$ and $NiMo /Al_2O_3\text{-}Mn$	Hydrodeoxygenation	Continuous Reactor, 380 °C, 4 MPa H_2, 35 mL/min H_2	43.8	Vázquez-Garrido et al. (2021)
Jatropha oil	Ru supported on alumina	Hydroprocessing	300 °C, 3 h, 4 MPa H_2, catalyst/oil weight ratio: 2.5/1	93	Kumar et al. (2022)
Jatropha oil	NiMo supported on Al_2O_3	Hydroprocessing	375 °C, 9 h, 4 MPa H_2	NA	Hussain and Biradar (2023)
Date palm seed oil	Mesoporous tantalum phosphate	Hydroprocessing	400 °C, 3 h, 1 MPa H_2, 15% of catalyst, 500 rpm	36	Rambabu et al. (2023)

NA Not available

multiple benefits to the bioeconomy, environment, and transport sectors.

Other authors have studied the use of cashew nutshell liquid as a raw material to prepare renewable diesel using different processes (e.g., hydroprocessing and hydrotreating) (Hapsari et al. 2020; Permata and Trisunaryanti 2020). Both Hapsari et al. (2020) and Permata et al. (2020) utilized different metals (Co and Ni, respectively) supported via wet impregnation of mordenite and evaluated their performance in the hydrotreatment of cashew nutshell liquid. Catalysts prepared by Hapsari et al. (2020) (Co/Mordenite) and Permata and Trisunaryanti (2020) (Ni/Mordenite) showed high catalytic activity, reaching similar renewable diesel conversions of 98.04 and 98.13%, respectively, under the same reaction conditions.

Yenumala et al. (2019) studied the hydrodeoxygenation of Karanja oil to produce renewable diesel using NiMo-alumina as a catalyst. Under the tested reaction conditions, an increase in the reaction temperature and metal content of the catalyst favored the hydrodeoxygenation process. The optimal operating conditions (Ni/Mo molar ratio of 0.9/3.4, 20 wt% catalyst, 340 °C, 4 h, and 3 MPa of H_2) allowed to obtain 100% conversion of oxygenated compounds. These authors emphasized that the catalyst was essential in the hydrodeoxygenation process for the effective production of renewable diesel made up of alkanes (C_{15}-C_{22}) chains, which were similar to those of petrodiesel and can be used directly in diesel engines without the need for blending.

Yulia and Zulys (2020) studied the hydroprocessing of kemiri sunan oil to produce renewable diesel. These authors prepared a NiMoCe/γ–Al_2O_3 catalyst and evaluated its performance. The hydroprocessing of this oil was carried out in a closed batch reactor at 400 °C for 5 h and 3.5 MPa, obtaining a maximum conversion of 58%. The incorporation of cerium on the catalytic surface favored the hydroprocessing of kemiri sunan oil and showed a better performance compared to other reported catalysts (e.g., sulfided NiMo/γ-Al_2O_3).

Muniyappan et al. (2023) studied the impact of operating temperature, blending ratio and catalyst addition on the renewable diesel composition via microwave co-pyrolysis of hydnocarpus de-oiled seed cake (HDSC) and waste electrical and electronic plastic (WEEP). These authors proposed a new approach of "treatment of wastes with waste" because the spent toner powder was converted into a low-cost catalyst via calcination at 600 °C to obtain magnetic Fe_3O_4 nanoparticles. Co-pyrolysis was carried out at operating temperatures of 450, 500, and 550 °C and HDSC:WEEP mixture ratios of 100:0, 75:25, 50:50, 25:75, 0:100. The results showed that the oil phase yield was higher when a 50:50 mixture ratio was used. This condition was established for the catalyst addition. The oil analysis showed that the oil produced had a high calorific value of 39.51 MJ/kg and a viscosity of 2.71 cSt, which were comparable to those of commercial diesel. The use of a catalyst notably decreased oxygen and nitrogen compounds and promoted the formation of aromatic hydrocarbons. Finally, techno-economic analysis revealed that a plant with a capacity of 1000 kg/h can be economically viable, with minimal production costs ($0.53/L in comparison to $1.15/L of commercial diesel in India).

Bioalcohols

The production of short-chain bioalcohols, such as ethanol and butanol, is generally carried out by the hydrolysis of a wide variety of lignocellulosic biomasses to obtain sugars (Jin et al. 2019), which are subsequently used in fermentation by different microorganisms (Gomes et al. 2019). *Saccharomyces cerevisiae* is the most popular yeast (Salafia et al. 2022) applied at an optimal temperature range of 30–35 °C (Kruasuwan et al. 2022) for bioethanol production, and *Clostridium acetobutylicum* and *Clostridium beijerinckii* (Pugazhendhi et al. 2019) for biobutanol production at an optimum temperature of 35–37 °C (Wu et al. 2021).

Chemical hydrolysis is the preferred method for obtaining sugars because it is an economical and fast process, unlike enzymatic hydrolysis, which can last days (Constantino et al. 2021). However, it depends on the raw material used; therefore, pretreatment methods can be combined to obtain better results. Table 3 reports recent studies on the use of biomass waste as feedstock for the production of bioalcohols.

Herein, it is convenient to highlight that the exploration of new sources of lignocellulosic biomass is fundamental. In this direction, Smuga-Kogut et al. (2019) proposed the use of lignocellulosic biomass obtained from areas that were excluded from agricultural production. Wastelands have diverse vegetation (e.g., grass and shrubs) with easy access, and their collection does not involve specialized equipment. These authors used ionic liquids (ILs) for lignocellulose pretreatment because these chemicals are environmentally friendly due to their low toxicity. The biomass was pretreated with 1-ethyl-3-methylimidazolium acetate (EMIMOAc) and 1-ethyl-3-methylimidazolium chloride (EMIMCl) to increase enzymatic hydrolysis. The mixture was then incubated at 120 °C for 2 h. Enzymatic hydrolysis was performed using commercial cellulase and fermentation with *S. cerevisiae*. The use of ILs has a positive impact by enhancing enzymatic hydrolysis. Finally, ethanol content also improved following the tendency: EMIMOAc (18.5 g/L) > EMIMCl (4.3 g/L) > untreated (0.32 g/L).

Aruwajoye et al. (2020) used cassava peel waste to obtain bioethanol via chemical hydrolysis using HCl and enzymatic hydrolysis using α-amylase and amyloglucosidase. The obtained sugar (0.58 g/g) was used by the yeast *S. cerevisiae* at 30 °C for 36 h to produce up to 0.53 g/g of bioethanol. Yusuf and Inambao (2019) employed only

Table 3 Recent studies of use of biomass waste as potential feedstock to produce bioalcohols

Waste	Pretreatment	Operational conditions for bioalcohol production	Concentration	References
Ethanol				
Pineapple fruit peel	Enzymatic hydrolysis: water for 2 days 2% *Trichoderma harzianum*, 30 °C, 48 h	*Saccharomyces cerevisiae,* 36 °C, 48 h	Total sugar: 172 g/L Ethanol: 6 g/L	Casabar et al. (2019)
Spirulina platensis biomass	Chemical hydrolysis: Sodium phosphate, freeze cycle -20 °C, 24 h and a defrost cycle 4 °C, 24 h Enzymatic hydrolysis: Saccharification: 1% of α-amylase and amyloglucosidase, 50 °C	*Saccharomyces cerevisiae* CAT-1, 30 °C, 20 h	Total sugar: 70 g/L Ethanol: 25 g/L	Rempel et al. (2019)
Agricultural wastelands (fireweed)	Chemical hydrolysis: 50 mL of 1-ethyl-3-methylimidazolium, 120 °C, 2 h	*Saccharomyces cerevisiae*, 4 days	Total sugar: 38 g/L Ethanol: 19 g/L	Smuga-Kogut et al. (2019)
Matooke peels (*Mbwazirume* and *Nakyinyika*)	Chemical hydrolysis: 1.5% H_2SO_4, 70 °C, 40 min	*Saccharomyces cerevisiae*, 33.39 °C, 20.21 h	*Mbwazirume:* total sugar: 77 g/L, ethanol: 72 g/L *Nakyinyika*: total sugar: 75 g/L, ethanol: 71 g/L	Yusuf and Inambao (2019)
Cassava peels waste	Chemical hydrolysis: 3.68% HCl, 69.68 °C, 2.57 h Enzymatic hydrolysis: 125.3 U/g α-amylase, 90 °C, 1 h 74.06 U/g amyloglucosidase, 60 °C, 24 h	*Saccharomyces cerevisiae* BY4713, 30 °C, 36 h	Total sugar: 0.58 g/g Ethanol: 0.53 g/g	Aruwajoye et al. (2020)
Sorghum biomass	Chemical hydrolysis: 1.5% NaOH, 90 °C, 5 h	30 FPU/g of flashzyme plus 200, 50 °C, 72 h *Saccharomyces cerevisiae*, 37 °C, 120 h	Ethanol: 506 L/ton of straw dry matter (L/mg)	Batog et al. (2020)
Potato peel wastes	Chemical hydrolysis: 3.68% HCl, 69.62 °C, 2.57 h, α-amylase, 90 °C, 1 h	*Saccharomyces cerevisiae* BY4713, 30 °C, 16 h	Ethanol: 23 g/L	Chohan et al. (2020)
Pumpkin peel	Enzymatic hydrolysis: 7.5 U/g α-amylase, 56.4 U/g amyloglucosidase, 2 h	*Saccharomyces cerevisiae,* 30 °C, 16 h	Total sugar: 51 g/L Ethanol: 84 g/L	Chouaibi et al. (2020)
Pomegranate peel	Chemical hydrolysis: 1% H_2SO_4, 121 °C, 0.25 h	*Kluyveromyces marxianus*, 30 °C, 24 h	Total sugar: 17 g/L Ethanol: 7 g/L	Demiray et al. (2020)

Table 3 (continued)

Waste	Pretreatment	Operational conditions for bioalcohol production	Concentration	References
Typha orientalis	Ionic liquids pretreatment: 4-(3-methyl-1-imidazolio)-1-butanesulfonic acid hydrogen sulfate, microwave power of 400 W, 1.5 g of catalyst, solvent volume 40 mL and 20 min	*Zymomonas mobilis,* 37 °C, 82 h	Ethanol: 52 g/L	Lin et al. (2021)
Spent mushroom from *Ganoderma lucidum*	Chemical hydrolysis: 10 mL of 1% H_2SO_4, 121 °C, 15 min	*Saccharomyces cerevisiae*, 30 °C, 5 days	Total sugar: 808 mg/g	Sudhakar et al. (2021)
			Ethanol: 1.6 g/L	
Raisin residue extract and biomass from cyanobacteria-based cultures	Chemical hydrolysis: 2.5 N H_2SO_4, 2 h	*Saccharomyces cerevisiae* strain AXAZ-1	Total sugar: 259 g/L	Tsolcha et al. (2021)
			Ethanol: 111 g/L	
Mixture of fruit waste (melon, pineapple, banana, apple, and mango)	Extraction solid/liquid using water, 50 °C	*Wickerhamomyces sp.*, 30 °C, 9 h	Total sugar: 36 g/L	Zanivan et al. (2022)
			Ethanol: 22 g/L	
Melon peel waste	Enzymatic hydrolysis: β-glycosidases, β-glucanases, pectinases, 40 °C	*Saccharomyces cerevisiae*, 40 °C, 48 h	Total sugar: 35 g/L	Rico et al. (2023)
			Ethanol: 56 g/L	
Potato mash and casuarina sawdust	Potato mash: TiO_2-Bi_2WO_6 under sunlight for 5 h. Casuarina sawdust: treatment under a 65 W fluorescent light source	*Saccharomyces cerevisiae,* 30 °C, 72 h	Potato mash: Ethanol: 3.5 g/L	Shiamala et al. (2023)
	Standard liquefaction by α-amylase		Casuarina sawdust: Ethanol: 29 g/L	
Biobutanol				
Apple pomace	Enzymatic hydrolysis: 290 μL of enzyme Cellic CTec2, 50 °C, 72 h, 180 rpm	*Clostridium beijerinckii* CECT, 500 °C, 96 h	Ethanol: 9 g/L	Hijosa-Valsero et al. (2017)
Cauliflower waste	Solid-to-liquid ratio of 1/10 (2% v/v H_2SO_4, 2% v/v HCl and 2% w/v NaOH), 121 °C, 60 min	*Clostridium acetobutylicum* NRRL B-527, 37 °C, 96 h	Ethanol: 3 g/L	Khedkar et al. (2017)
Organic fraction of municipal solid waste	Chemical hydrolysis: 21.7 g of organic fraction of municipal solid waste, 195 mL of 85% v/v ethanol/water solution and 0.5% w/w H_2SO_4, 120 °C, 0.5 h	1 g/L yeast extract and 3 g/L peptone, 37 °C, 96 h	Ethanol: 5 g/L	Farmanbordar et al. (2018)
	Enzymatic hydrolysis: 9/1 ratio of Cellic® CTec2 (cellulase) and Cellic® HTec2 (hemicellulose), 1.5 g of material, 121 °C, 20 min			

Table 3 (continued)

Waste	Pretreatment	Operational conditions for bioalcohol production	Concentration	References
Industrial potato peel	Autohydrolysis: 140 °C, 56 min, 10% (w/w) potato peel)	*Clostridium saccharoperbutylacetonicum* DSM 2152, 35 °C, 120 h, S: 100 rpm	Ethanol: 8 g/L	Hijosa-Valsero et al. (2018)
	Enzymatic hydrolysis: 50 °C, 72 h, pH 5, 290 uL Cellic CTec2 and 100 uL Spirizyme fuel, 10 g solid biomass			
Pea pod waste	Chemical hydrolysis: 1 g of sample, 5 mL H_2SO_4 1.3% (v/v), 121 °C, 0.25 h	*C. acetobutylicum* B-527, 37 °C, 96 h	Ethanol: 4 g/L	Nimbalkar et al. (2018)
Mixture of plant biomass[1]	Washed with deionized water, dried (60 °C, 24 h)	*C. acetobutylicum MTTCC,* sonification at 35 kHz, 92 h	Ethanol: 0.233 g/g	Borah et al. (2019)
	Acid hydrolysis (H_2SO_4 1% v/v, 121 °C, 0.5 h), alkaline delignification (1.5% w/v NaOH, 30 °C, 10 min) and enzymatic hydrolysis (cellulase and *β*-glucosidase enzymes)			
Spent coffee grounds	Chemical hydrolysis: 5 g spent coffee grounds and 50 mL H_2SO_4, microwave-assisted	*Clostridium beijerinckii*, 48 h	Ethanol: 7.7 g/L	López-Linares et al. (2021)
Orange waste	Hydrothermal: Orange waste/Water ratio: 1/10 (w/w), 100 °C, 0.5–1 h	*Clostridium acetobutylicum* NRRL B-591, 37 °C, 72 h, 160 rpm	Ethanol: 43 g/Kg OW	Saadatinavaz et al. (2021)
	Enzymatic hydrolysis: Cellic® CTec2 (cellulase) and Cellic® HTec2 (hemicellulose), 45 °C, 72 h, 140 rpm			
Sugar beet pulp	Microwave-assisted extraction, 165 °C, 12 min	*C. beijerinckii,* 35 °C, 48 h, 135 rpm	Ethanol: 8.3 g/L	Del Amo-Mateos et al. (2022)
Cellulosic residue of sweet potato	Chemical hydrolysis: 1% (v/v) H_2SO_4, 115 °C, 0.5 h	*Clostridia acetobutylicum* CICC, 37 °C, 48 h	Ethanol: 8 g/L	Jin et al. (2022)
	Enzymatic hydrolysis: xylanase, pH 4.5, 30 °C, 10 min			
Carrot discards	Chemical hydrolysis: 10 w/w of carrot discards, 121 °C, 0.25 h	*Clostridium beijerinckii* DSM 6422, 35 °C, 48 h	7.4 g/L	López-Linares et al (2023)
	Enzymatic hydrolysis: substrate loading: 10% (w/w), 50 °C, 24 h, 150 rpm, pH: 4.8, Cellic CTec2, Viscozyme L, Shearzyme			

Table 3 (continued)

Waste	Pretreatment	Operational conditions for bioalcohol production	Concentration	References
Industrial tea waste	Chemical hydrolysis: Milled industrial tea waste (300 g/L), 1% H_2SO_4 (v/v), 121 °C, 0.25 h	*Clostridium beijerinckii* DSMZ 6422, 37 °C, 96–120 h	6.21 g/L	Tekin et al. (2023)

[1] Mixture of plant biomass: *Arundo donax, Chromolena odorata, Eichhornia crassipes, Ipomea carnea, Lantana camara, Mikania micrantha, Parthenium hysterophorus and Saccharum spontaneum*

the chemical hydrolysis of matooke peels from two species (Mbwazirume and Nakyinyika) with sulfuric acid (1.7%) at 70 °C for 40 min to obtain a total sugar of 77.03 g/L with the Mbwazirume species and 75.32 g/L with the Nakyinyika species. This sugar fermentation achieved up to 71.54 and 70.57 g/L of bioethanol, respectively. In addition, Chouaibi et al. (2020) opted for a single enzymatic hydrolysis of pumpkin peel using α-amylase and amyloglucosidase to obtain up to 84.36 g/L of bioethanol.

Watermelon rind (WMR) biomass was used as feedstock to produce ethanol via integrated and combinative sequential ultrasonication and deep eutectic solvent (DES) pretreatment, enzymatic hydrolysis, and fermentation (Fakayode et al. 2021). Note that DESs are inexpensive, easy to prepare, renewable, biocompatible, and biodegradable; thus, they are suitable for different applications. In this study, the DES was prepared using choline chloride and lactic acid. On the other hand, ultrasonication allows chemical reactions under mild conditions with reduced power requirements. The results indicated that the ethanol yield ranged from 0.276 to 0.458 g/g of raw WMR, with fermentation efficiencies of 54.12–89.80%, respectively. The maximum efficiencies were obtained using an ultrasonication power of 180 W, frequency of 40 kHz, time of 40 min, and DES reaction temperature of 120 °C for 180 min. The combined pretreatment favored the delignification, solubilization, and hydrolysis of cellulose and hemicellulose into monomeric sugars.

Although chemical and enzymatic hydrolysis are the most popular and commonly used methods, other processes and microorganisms have been explored. They include solid/liquid extraction with water to obtain sugars from different fruit residues (e.g., melon, pineapple, banana, apple, and mango) and the use of *Wickerhamomyces* sp. for fermentation (Zanivan et al. 2022). This process generated up to 21.63 g/L of bioethanol.

Biobutanol is an important fuel used in internal combustion engines (López-Linares et al. 2021) as well as a solvent and extractant (Hijosa-Valsero et al. 2018). Consequently, several types of biomass wastes have been studied as precursors for this biofuel. The biomass used for this purpose includes industrial tea waste (ITW) (Tekin et al. 2023), spent coffee grounds (SCG) (López-Linares et al. 2021), pea pod waste (Nimbalkar et al. 2018), and apple pomace (Hijosa-Valsero et al. 2017). For example, Hijosa-Valsero et al. (2017) studied apple pomace, which is the residue after juice extraction, as feedstock to produce biobutanol. Note that it has been estimated that the global apple production was approximately 84 million tons in 2014. Five soft physicochemical pretreatments (autohydrolysis, acids, alkalis, organic solvents, and surfactants) were tested in a high-pressure reactor, with subsequent traditional enzymatic treatment and fermentation with *Clostridium beijerinckii*. Nitric acid was the best reagent to pretreat biomass at 120 °C. The analysis demonstrated 91% of sugar consumption confirming its effectiveness to produce 3.55 g/L of acetone, 9.11 g/L butanol and 0.26 g/L ethanol. In contrast, Tekin et al. (2023) and López-Linares et al. (2021) used ITW and SCG, respectively, in a similar process to obtain biobutanol yields up to 6.21 and 7.7 g/L. In both studies, the biomass was subjected to chemical hydrolysis with sulfuric acid, followed by fermentation with *Clostridium beijerinckii*. Nimbalkar et al. (2018) also used sulfuric acid to carry out the hydrolysis of pea pod waste. However, the yield of this process was lower than that reported in other studies since they only obtained 3.82 g/L of biobutanol using *Clostridium acetobutylicum*.

The increasing global demand for cocoa has led to a high generation of cocoa pod husks as waste. Muharja et al. (2023) tested the potential of this biomass to produce biobutanol. Various treatments such as ultrasonic-assisted pectin extraction, microwave-assisted delignification, enzymatic hydrolysis with surfactant addition, and extractive fermentation using immobilized cells with reducing agent supplementation have been studied. This sequential process resulted in a high butanol concentration of 20.4 g/L.

Bio-oil

Lignocellulosic biomass is an important raw material in bio-oil production (Li et al. 2021). Various vegetable materials are rich in esters, aldehydes, ketones, and other important functional groups (Li et al. 2021). Therefore, selection of a suitable biomass feedstock is crucial to obtain this bioproduct. Table 4 lists relevant studies on bio-oil production from waste biomass.

Li et al. (2021) studied the bio-oil production from *Aesculus chinensis* Bunge Seed (ACBS) via catalytic pyrolysis with Fe_2O_3 and NiO. ACBS sample was previously treated with $NaHCO_3$. The pyrolysis products consisted of aldehydes, ketones, acid esters, alcohols, and hydrocarbons. In particular, 1-hydroxy-2-propanone (3.97%), acetic acid (5.42%), and furfural (0.66%) were recovered for their use as chemical feedstock in the form of bio-oil. It was noted that the catalysts enhanced pyrolysis by accelerating the precipitation of gaseous compounds. The combination of ACBS waste and nanocatalysts could address the valorization of agricultural and forestry waste.

Catalytic fast pyrolysis (CFP) using HZSM-5 was employed to obtain bio-oil from eucalyptus wood (Promsampao et al. 2022). The ex situ CFP in a fluidized bed reactor strategy has a high potential to produce deoxygenated bio-oil in a single process. The use of a catalyst enhanced the bio-oil yield to achieve a maximum of 11.4 wt% and low oxygen content (< 4.3 wt%) resulting in 93% oxygen removal.

Xiong et al. (2023) proposed the use of natural hair waste (HW) and corn straw (CS) as feedstock to produce bio-oils. Human hair waste can be classified as municipal solid biowaste. HW and CS pyrolysis was performed in a tubular furnace at 450 °C. The co-pyrolysis of CS was carried out under different HW loads. The highest bio-oil yield (48%) was obtained with the HW load (21%). Therefore, an increase in the HW ratio of the blend favored the bio-oil yield. It was observed that the mixture of CS and HW for co-pyrolysis provided a more complex-structured bio-oil than individual pyrolysis. Bio-oils contained 93 and 89 compounds in CS and HW oils, respectively, which increased to 107 compounds in the blend.

Bio-oils have a high oxygen content and require further upgrading prior to use. Therefore, Zhang et al. (2023) tested the catalytic reforming of bio-oil during rice straw pyrolysis using a calcium-containing catalyst. The results demonstrated that the use of a catalyst in the rice straw pyrolysis affected the chemical composition of the bio-oil, where ketones, furans, alcohols, and phenols were obtained.

Xue et al. (2023) proposed a novel technology that coupled formaldehyde-pretreatment (FA) and catalytic fast pyrolysis of poplar sawdust to solve the problem of low hydrocarbon yields. This interesting technology (FACFP) introduced a catalyst in the pretreatment stage, favoring the dissolution of lignin and its conversion. The effects of pretreatment variables, such as solvents, temperature, and processing time, on bio-oil yield were studied. The use of FA as a pretreatment solvent in comparison with water allowed lignin removal and enhanced the accessibility of cellulose to the catalyst during pyrolysis. FA pretreatment resulted in a 70% oil yield. SEM micrographs revealed that the increase in pretreatment temperature caused the fragmentation of biomass owing to the dissolution of hemicellulose and lignin in the filtrate. The chemical compounds in the bio-oil were hydrocarbons, phenols, and carbonyls. The coupling FACFP technology significantly improved hydrocarbon selectivity (1.7-fold for the two-step FA + CFP). The use of HZSM-5 enabled the deoxygenation of phenols and carbonyls to hydrocarbons during pyrolysis.

Bio-oil production from non-edible *Reutealis trisperma* oil (RTO) by catalytic pyrolysis was carried out using dolomite (a sedimentary carbonate rock) as catalysts (Buyang et al. 2023). It is noteworthy that *Reutealis trisperma* seeds contain 50–50% of oil. The results showed that an increase in pyrolysis temperature (400–450 °C) enhanced bio-oil yield from 60 to 77%, with low char formation, while non-catalytic pyrolysis produced 68% bio-oil with 7% of char. The use of dolomite enhanced the composition of heavy hydrocarbon molecules, as reflected in a bio-oil with a higher flash point, thermal stability, calorific value, density, and low viscosity. Additionally, the bio-oil quality improved with esterification, thus reducing the carboxylic acid content from 55 to 3%.

Water hyacinth (*Eichhornia crassipes*) is an invasive weed common in lakes, ponds, and rivers because it forms

Table 4 Recent studies of use of biomass waste as potential feedstock to produce bio-oil

Waste	Catalyst	Process	Operating conditions	Yield or Conversion, %	References
Loblolly pine	–	Fast pyrolysis	100 g of biomass, 500 °C, 12 L/min N_2, 1.5 s, biomass feeding rate: 150 g/h	Oxygen to carbon atomic ratio: 0.63	Meng et al. (2012)
				Bio-oil: 74 (oxygen %) / 58 (carbon %)	
Pitch pine (*Rigida pine* P. Mill)	—	Pyrolysis	Biomass particle size: 0.55 mm, 500 °C, 10 L/min N_2, biomass feeding rate: 100 g/h,	66	Tran et al. (2021)
Pine sawdust	Pt-Ni/Al	Pyrolysis	0.5 mg of biomass, 450 °C, 500 °C, 0.3 min, 5 mg of catalyst	15–23	Zheng et al. (2021)
Corncob	HZSM-5/activated carbon	Catalytic pyrolysis	3 g of biomass, 500 °C, 40 min, 5 mL/min, HZSM-5/activated carbon ratio: 2/1, catalyst/biomass ratio: 1/1	44	Duan et al. (2022)
Pistacia lentiscus L seeds	—	Pyrolysis	20 g of biomass, 475 °C, heating rate of 25 °C/min, particle size: 0.3–0.6 mm	64	Farissi et al. (2022)
Date seed and plastic waste	—	Co-pyrolysis	100 g of date seed, 70 g of plastic, 500 °C, heating rate of 50 °C/min, 100 mL/min N_2, 12.5 MPa, 1200 rpm	59	Inayat et al. (2022)
Food and plastics waste	—	Co-pyrolysis	Batch Reactor, 200 g of biomass, 400 °C, 1 h, food waste/plastic constant ratio: 2/1	Fish bone + plastic: 16	Lim et al. (2022)
				Chicken bone + plastic: 20	
				Rice + plastic: 29	
Eucalyptus wood	HZSM-5 in white extrudate form with SiO_2/Al_2O_3 ratio of 30	Catalytic fast pyrolysis	500 °C, 1.5 h, 11 L/min, fluidized bed reactor: 160 g/h, biomass/catalyst mass ratio: 0.4	11	Promsampao et al. (2022)
Linseed residue	–	Pyrolysis	50 g of biomass, 500 °C, 1.5 h, 200 cm^3/min, heating rate: 20 °C/min	79.64	Bahadorian et al. (2023)
Reutealis trisperma oil	–	Pyrolysis	Non-catalytic, reactor semi-batch, 450 °C, 190 min	68	Buyang et al. (2023)
	Dolomite		Catalytic, dolomite/ *Reutealis trisperma* oil mass ratio: 1/10	77	
Sawdust and rice husk	–	Co-pyrolysis	Fluidized bed reactor, 500 °C, 20 L/min, blending ratio of sawdust/rice husk: 50/50	52	Fadhilah et al. (2023)

Table 4 (continued)

Waste	Catalyst	Process	Operating conditions	Yield or Conversion, %	References
Biomass of water hyacinth	–	Hydrothermal liquefaction	Impregnation of biomass of water hyacinth with $CuCl_2$ 0.2 M Hydrothermal liquefaction: Cu-impregnated biomass of water hyacinth/water ratio of 1/9, 270 °C, 0.5 h	83	Gao et al. (2023)
Municipal (household) and horticultural wastes	ZSM-5	Co-pyrolysis	50 g of biomass, waste blends (0–100 wt%), 550 °C, 1 min, 200 mL/min N_2, 0–15% of catalyst	58	Ghorbannezhad et al. (2023)
Corncob	–	Hydrothermal liquefaction	300 °C, 0.25 h, 10 mL/min	10	Martins-Vieira et al. (2023)
Hydnocarpus de-oiled seed cake, waste electrical and electronic plastic	Fe_3O_4 (waste toner powder derivative)	Microwave co-pyrolysis	Hydnocarpus de-oiled seed cake /Waste electrical and electronic plastic weight ratio: 50/50 (g/g), 500 °C, 10 g of catalyst, heating rate of 30 °C/min, microwave power of 1100 W	26	Muniyappan et al. (2023)
Cassava residue	–	Pyrolysis	500 °C, 1–2 h, 0.5–3.5 L/min N_2, fluidized bed reactor: 100 g/h	54	Rueangsan et al. (2023)
Lychee	–	Pyrolysis	350 °C, 125 min, heating rate of 120 °C/min, 110 mL/min Ar	38	Singh et al. (2023)
Rice husk	–	Co-pyrolysis	80 g of biomass, 650 °C, 1800s, heating rate of 9750 °C/h	38	Wakatuntu et al. (2023)
Corn straw and hair waste	–	Pyrolysis/Co-pyrolysis	5 g of biomass, corn straw/hair waste blend ratio: 25/75% (w/w), 450 °C, 20 min, 80 mL/min	Corn straw: 10 Hair waste: 48 Corn straw/hair waste: 46	Xiong et al. (2023)

impenetrable nets that affect aquatic life and obstruct waterways (Gao et al. 2023). It has been determined that its growth is accelerated (0.26-ton dry biomass per day), and infestations are often difficult to remove. Therefore, the valorization of this biomass is an alternative method to resolve these issues. Gao et al. (2023) evaluated the hydrothermal liquefaction of WH impregnated with Cu and Co to improve the bio-oil yield. The use of Cu resulted in a higher bio-oil yield than that obtained with Co. The impact of the reaction parameters (e.g., reaction residence time, temperature, and biomass-to-water ratio) was also evaluated. The water-to-biomass ratio considerably tailored the bio-oil yields. The optimal conditions were identified as 0.2 M-Cu-impregnated-WH, 1:9 biomass-to-water ratio, 270 °C, and 30 min to achieve the highest bio-oil yield of 41 wt% with a conversion of 83%. The chemical composition of the bio-oil mainly consisted of N-containing and phenolic compounds.

Bio-jet

The hydrocarbon-like jet fuel obtained from renewable biomass exhibits a satisfactory combustion performance for engines and contributes to reduce COx emissions (Ravindran et al. 2022). Table 5 illustrates the use of different biomass waste as feedstock to produce bio-jet. Recent advances in the production of this biofuel are described below.

Chu et al. (2017) modeled the hydrodeoxygenation of the oilseeds camelina, carinata (non-edible oil), and WCO to produce bio-jet. Data were collected from the literature. The effect of feedstock composition and condition parameters on product yields and distribution, hydrogen consumption, and process utilities were analyzed. The model considered feedstock production, oil extraction, oil conversion, and product recovery. The results showed that the hydrogen consumption ranged from 26 to 30 kg/ton of input oil and depended on unsaturation chemistry. The thermal energy requirement was 2.8 GJ/ton for WCO, 5.2 GJ/ton for carinata and 5.7 GJ/ton for camelina. Note that the highest energy consumption for camelina processing was due to the high energy required for oil extraction. The electricity consumption was 73 kWh/ton for WCO, 170 kWh/ton for carinata, and 227 kWh/ton for camelina, respectively.

The catalytic cracking of WCO to produce bio-aviation fuel has been studied by El-Araby et al. (2020). Zinc aluminate was used as a catalyst and WCO exhibited low acidity and the presence of unsaturated C = C as linoleic acid. The optimal reaction conditions were 450 °C, 120 bar, 2.5% (w/v) catalyst dose, reaction time of 60 min, and H_2 pressure of 4 atm. Thermal cracking of WCO under optimum conditions yielded 96% crude biofuel and, after distillation at 120–250 °C, 49% bio-jet was obtained. The bio-jet was composed of 83% paraffin.

Altalhi et al. (2021) obtained bio-jet from WCO and jatropha oil via catalytic cracking with thermal agitation at 450 °C for 4 h using modified-montmorillonite as catalyst. The products were then recovered via condensation. The characteristics of the bio-jet were determined, and the fatty acid content was found to be similar for both oil feedstocks. The bio-jets were blended with petro-JET A1, and the most efficient mixture was 10% bio-jet and 90% JET A1, which met ASTM specifications.

A continuous fixed-bed reactor was used for catalytic deoxygenation of palm kernel oil to produce a bio-jet (Makcharoen et al. 2021). A Pd catalyst supported on activated carbon was packed into a tubular reactor. The results demonstrated a bio-jet yield of 58%, which contained 27.68% of linear alkanes in the jet fuel (C_8-C_{16}) range with a productivity of 9.32 g of product per g of catalyst. This yield was achieved under optimal operating conditions (420 °C, 500 psi, H_2 flow rate of 17.50 mL/min, and 0.07 g of catalyst). The oxygen content was successfully reduced from 19% (in oil) to 15% (in the bio-jet).

Orange tree is the most widely cultivated fruit tree in the world, contributing approximately 60% of the 100 Mt per year of citrus produced globally (Erukainure et al. 2016). The orange juice industry produces 30 Mt of waste annually (Donoso et al. 2022). The orange peels were subjected to oil extraction using steam distillation. The potential use of orange oil as a bio-jet precursor was studied by Donoso et al. (2022). The raw orange oil extraction yield was 4.9 wt% on a dry basis and contained 44.6 wt% of D-limonene. The D-limonene molecular structure suggested that it could ideally work as a blend component for Jet A1 because the carbon number is in the Jet A1 range, and it is a cyclic alkene. To enhance its fuel properties, especially to decrease its soot tendency, the oil was hydrogenated to be industrially viable. Hydrogenation was performed in a closed reactor filled with H_2 at 60 °C for 5 h to obtain a conversion of 50%. Key physicochemical parameters including the density, viscosity, heating values, lubricity, flash point, crystallization onset temperature, and smoke point were measured. The properties of hydrogenated orange oil indicated that this is a potential alternative for blending up to 15 vol% with Jet A1, fulfilling all the ASTM requirements.

Ahmed et al. (2022a) obtained bio-jet from WCO using catalytic pyrolysis where functionalized montmorillonite/chitosan nanocomposites were used as catalyst. A split-type tubular semi-batch reactor was used to perform the pyrolysis. The pyrolytic product exhibited chemical characteristics comparable to those of the bio-jet. The optimum conditions for producing the bio-jet were 0 catalyst ratio of 0.7%, reaction time of 120 min, and temperature of 300 °C. The use of a catalyst determined the selectivity and quality of the final product.

Table 5 Recent studies of use of biomass waste as potential feedstock to produce bio-jet

Waste	Catalyst	Treatment	Reaction conditions	Yield or Conversion, %	References
Waste soybean oil and palm fatty acid distillate	Pd-based zeolite	Catalytic conversion	270 ℃, 3 h, 1.5 MPa, 10 g of reactant, 2.5 g of catalyst	31	Choi et al. (2015)
Camelina sativa, *Brassica carinata* and Used cooking oil	NiMo	Hydrodeoxygenation	400 °C, 2 h, 9.2 MPa	53–54	Chu et al. (2017)
Pretreated-Waste cooking oil	NiMo/γ-Al_2O_3-β-zeolite	Catalytic hydrodeoxygenation	350 °C, 5 MPa, 3 h, 0.1 g of catalyst, pretreated-waste cooking oil/solvents (tetralin and dodecane) w/w ratio: 1/4	98	Li et al. (2018b)
Palm oil	Y	Deoxygenation (decarboxylation and decarbonylation, catalytic cracking)	Batch reactor, 150 mL palm oil, Oil/catalyst mass ratio: 20/1, 390 °C, S: 300 rpm	91	Basir et al. (2019)
	ZSM-5			74	
	Y-ZSM-5 composite			96	
	Y/ZSM-5 hybrid			99	
Waste cooking oil	$ZnAl_2O_4$	Catalytic hydrocracking	Batch reactor, 450 °C, 1 h, 12 MPa, 2.5%w/v of catalyst, pressure initial of 0.4053 H_2	49	El-Araby et al. (2020)
Wastes plastic and fir Douglas	Fe/activated carbon	Catalytic Co-pyrolysis	500 °C, catalyst/feedstock ratio: 1, 50 mL/min N_2	54	Lin et al. (2020)
Wastes plastic and fir Douglas	Sulfonated activated carbon-based	Catalytic Co-pyrolysis	500 °C, 0.25 h, 160–170 mL/min N_2, 3 g of catalyst	98	Mateo et al. (2020)
Macauba acid oil	Co/activated carbon	Deoxygenation	350 °C, 4 h, 3 MPa H_2	98	Moreira et al. (2020)
Jatropha curcas oil and Waste cooking oil	Montmorillonite-3-mercaptopropyl trimethoxy silane-SO_3H	Pyrolysis	150 mL of *Jatropha curcas* oil, 350 °C, 4 h, 0.2–1% of catalyst, catalytic cracking: 250 °C	NA	Altalhi et al. (2021)
			150 mL waste cooking oil, 350 °C, 4 h, 0.2–1% of catalyst, catalytic cracking 250 °C		
Palm kernel oil	Pt/activated carbon	Deoxygenation	420 °C, 3.45 MPa, 17.5 mL/min H_2, palm kernel oil flow of 0.02 mL/min, 0.07 g of catalyst	83	Makcharoen et al. (2021)
Palm kernel oil	Pd/activated carbon	Deoxygenation	400 °C, 2 h, 8% of catalyst	96	Why et al. (2021)
Waste cooking oil	Activated montmorillonite clay	Pyrolysis	300 °C, 2 h, 0.7% of catalyst	NA	Ahmed et al. (2022a, b)
	Activated montmorillonite clay modified with chitosan biopolymer		400 °C, 3 h, 0.8% of catalyst	NA	
Tung oil	Co-W/silica- alumina	Deoxygenation-cracking	350 °C, 2 h, N_2 atmosphere, 5% of catalyst	69	Asikin-Mijan et al. (2022)

Table 5 (continued)

Waste	Catalyst	Treatment	Reaction conditions	Yield or Conversion, %	References
Palm oil	Ni/desilicated mesoporous zeolites (Hbeta, USY, NH_4-ZSM-5)	Hydroprocessing	425 °C, 2.5 MPa, 10% of catalyst	57	Panarmasar et al. (2022)
Palm kernel oil	FeMo/activated carbon	Deoxygenation	250 °C, 0.5 h, 5% of catalyst, microwave system	80	Ravindran et al. (2022)
Polyisoprene rubbers	Pt/activated carbon	Hydropyrolysis Hydrogenation	460 °C, 0.2 MPa H_2, 110 mL/min H_2	64	Wang et al. (2022b)
Date palm seed oil	Tantalum phosphate	Dehydrogenation	400 °C, 3 h, 1 MPa H_2, 15% of catalyst	54	Rambabu et al. (2023)

NA Not available

Recent advances on the preparation of catalysts from biomass and their application in biofuel production

Homogeneous catalysts are effective and inexpensive for use in diverse reactive systems. However, their utilization also exhibits environmental and technical drawbacks such as a large volume of waste, corrosion of equipment, difficult separation from mixtures, and environmental pollution (Mateo et al. 2020). Heterogeneous catalysts can overcome several of these drawbacks because they offer easy separation, recycling, and reuse, which are beneficial in terms of energy-saving and environmental impact (Mateo et al. 2020).

In recent years, the number of catalysts obtained from biomass has considerably increased (Li et al. 2023). Both cost and environmental factors have encouraged the use of green catalysts derived from natural sources. Biomass-based catalysts are of great interest because they add value to the waste and guarantee a sustainable catalyst production. The residues used for the preparation of these materials include agricultural (shells, leaves, stems, seeds, etc.) (Verma et al. 2012), corals, animal bones, chitosan waste (Si et al. 2017), biomass ash, and carbon materials (Mateo et al. 2020). The catalysts derived from carbonaceous materials have been intensively investigated because they can be easily prepared and are less expensive than other supports (Mateo et al. 2020). Note that these carbon-based materials offer large surface areas, wide pore distribution, thermal stabilities, embedded functional groups, and tunable physicochemical properties that can be tailored for the application at hand (Zhang et al. 2019). Depending on the preparation methodology, biochar, hydrochar, or activated carbon can be obtained, which can offer specific physicochemical characteristics as catalyst supports. In this section, the preparation and application of heterogeneous carbon-based catalysts for the production of various biofuels are discussed.

Biodiesel

Catalysts in the transesterification process are responsible for starting the reaction and stimulating the solubility of the alcohol in the oil, subsequently increasing the reaction speed and biodiesel yield. Catalysts are also important in pyrolysis and other thermochemical technologies, where the use of waste biomass contributes to reducing costs and enhancing the availability of this type of biodiesel (Nayab et al. 2022). Table 6 shows the use of biomass waste as a catalyst precursor for biodiesel production where different catalysts are discussed in this subsection.

Calcium oxide (CaO) is a basic heterogeneous catalyst for oil transesterification because of its catalytic activity,

Table 6 Recent studies of biomass-derived catalysts to produce biodiesel

Waste	Treatment	Conditions for catalyst preparation	Reaction conditions	Yield or Conversion, %	References
Goat bone	Thermal	Calcination temperature of 900 °C, 3 h	Methanol/oil ratio: 11/1, 60 °C, 3 h, 2% of catalyst	92	Mamo and Mekonnen (2019)
Corncobs	Thermochemical	H_3PO_4, 3 min, 25 °C Carbonization temperature of 500 °C, 1 h	Methanol/oil ratio: 6/1, 75 °C, 0.3 h, 20% of catalyst, microwave power of 240 W	89	Rocha et al. (2019)
Carica papaya stem	Thermal	Calcination temperature of 700 °C, 4 h	Waste cooking oil and *Scenedesmus obliquus* lipid, Methanol/oil ratio: 9/1, 60 °C, 3 h, 2% catalyst	Waste cooking oil: 95 *Scenedesmus obliquus* lipid: 93	Gohain et al. (2020)
Ostrich (*Struthio camelus*) bones	Thermal	Calcination: 900 °C, 4 h	Waste cooking oil, Methanol/oil ratio: 15/1, 60 °C, 4 h, 5% of catalyst	91	Khan et al. (2020)
Moringa leaves	Thermal	Calcination: 500 °C, 2 h	Methanol/oil ratio: 6/1, 65 °C, 2 h, 6% of catalyst	87	Aleman-Ramirez et al. (2021)
Sargassum oligocystum alga	Thermochemical	Biomass drying: (100 °C, 48 h) Biochar preparation: (350 °C, 2 h, heating rate 5 °C/min) CaO production: (eggshell calcination, 850–900 °C, 4 h) Modification: K_2CO_3 1.5%, 20 min, biochar and CaO ratio: 1/1 w/w, stirred (85–90 °C, 5 h) Calcination: 500 °C, 3 h	65 °C, 200 min, methanol/oil ratio: 18/1, 4% of catalyst	99	Foroutan et al. (2021)
Wheat bran	Thermochemical	Calcination: 700 °C, 4 h. CaO treatment	Waste cooking oil, Methanol/oil ratio: 46/1, 54.6 °C, 1.9 h, 11.66% of catalyst	94	Gouran et al. (2021)
Acai seed	Thermal	Calcination: 800 °C, 4 h	Methanol/oil ratio: 18/1, 100 °C, 1 h, 12% of catalyst	99	Mares et al. (2021)
Sugarcane bagasse	Thermochemical	Partial carbonization and sulfonation with H_2SO_4, 200 °C, 4 h	Waste cooking oil, methanol/oil ratio 18/1, 60 °C, 0.25 h, 15% of catalyst	89	Nazir et al. (2021)
De-oiled microalgal biomass	Thermochemical	Carbonization: 600 °C, 4 h Sulfonation: 15 ml of H_2SO_4, 6 h	Waste cooking oil and microalgal oil, methanol/oil ratio: 11/1, 60–70 °C, 6–8 h, 4% of catalyst	Waste cooking oil: 96 Microalgal oil: 94	Roy and Mohanty (2021)
Empty fruit bunch	Thermochemical	Carbonization:200 °C for 24 h. 100 mL of 20% of H_3PO_4 for 6 h	Waste cooking oil, methanol/oil ratio: 12/1, 70 °C, 2 h, 5% of catalyst	97	Abdullah et al. (2022)

Table 6 (continued)

Waste	Treatment	Conditions for catalyst preparation	Reaction conditions	Yield or Conversion, %	References
		600 °C for 3 h			
Garlic peel	Thermochemical	Carbonization: 350 °C, 2 h. Sulfonation: H_2SO_4, 105 °C, 2 h	Methanol/oil ratio: 10/1, 60 °C, 3.5 h, 8% of catalyst	96	Wei et al. (2022)
Banana Pseudostem (Dwarf Cavendish)	Thermal	Pyrolysis: 35 g of biomass at 500 °C Calcination: 30 g of biochar, 700 °C, 3 h	60 °C, 2 h, methanol/oil ratio: 9.35/1, 4.7% of catalyst	98	Daimary et al. (2023)
Banana peel	Thermal	Calcination: 700 °C, 4 h	Methanol/oi ratio: 6/1, 5 °C, 1.5 h, 2% of catalyst	98	Husin et al. (2023)
Karanja seed shell	Thermal	Calcination: 650 °C, 4 h	Methanol/oil ratio: 10/1, 65 °C, 1 h, 2% of catalyst	96	Prajapati et al. (2023)
Rice husk	Thermochemical	Pyrolysis temperature: 700 °C, 3 h, N_2 Charred rice husk with KOH: 1 M at a ratio of 1/10 (wt/vol), 105 °C, 3 h 0.2 g $FeCl_3$ and $ZnCl_2$, 25 °C, 3 h Pyrolysis: 600 °C, 2 h, N_2 Modification with H_2SO_4	Methanol/oil ratio: 16/1, 74.8 °C,4.8 h, 9.9% of catalyst	98	Saidi et al. (2023)
Pyrolysis					
Seaweed	Thermochemical	500 °C, 1.5 h, N_2 atmosphere KOH Carbonization: 800 °C, 1 h, N_2 atmosphere Modification: $Cu(NO_3)$	Catalytic pyrolysis: 550 °C, 0.2 L/min N_2, 10 g of oil, 15% of Cu/Carbon (catalyst)	91	Yuan et al. (2021)

long functional life, mild reaction conditions, non-toxicity, low solubility in methanol, and basic strength. It has been found that calcium-containing metal oxides are easier to separate from the products (Kawashima et al. 2008) and have high reactivity with water producing calcium hydroxide. The production of CaO from waste shells rich in calcium, such as shells, chicken eggshells (Pavloviç et al. 2021; Ashine et al. 2023), ostrich eggshells (Chen et al. 2014), palm kernel shell gasification residues (Bazargan et al. 2015), oyster shells (Shobana et al. 2021), snail shells (Laskar et al. 2018), and cockle shells (Boey et al. 2011), has been an interesting and environmentally friendly option. Animal bones are another source of CaO because they are composed of 40% of calcium phosphate, beta-tricalcium phosphate, and natural hydroxyapatite. Hydroxyapatite has a surface area of 83 m^2/g, low crystallinity, and high thermal stability. Thus, it can be used as a support and catalyst. The most widely used process for obtaining CaO from these residues is calcination at > 850 °C, but not at temperatures higher than 1000 °C (due to the significant reduction in the surface area). Previous studies have demonstrated that the basicity and surface area of this oxide increased as the temperature of the thermal treatment also increased (Suwannasom et al. 2016).

Several authors have used animal bones such as bovine bones (Ayodeji et al. 2018), chicken (Suwannasom et al. 2016) and ostrich (Khan et al. 2020) to prepare catalysts for oil transesterification. Suwannasom et al. (2016) studied the transesterification of used cooking oil with CaO derived from the calcination of waste chicken bone at 800 °C and obtained a yield of 96.31%. A lower concentration of biodiesel was obtained with catalysts prepared at lower calcination temperatures. Ayodeji et al. (2018) obtained a calcium oxide catalyst from cow bones and soybean oil with a reaction time of 3 h at 60 °C and a yield of 93%.

Khan et al. (2020) utilized ostrich waste calcined at 600–1000 °C for the catalyst preparation. The transesterification conditions were 60 °C, a 15:1 methanol-to-oil molar ratio, a reaction time of 4 h, and a catalyst loading of 5 wt%. XRD analysis showed that the crystallinity increased with calcination temperature, where CaO and $Ca(OH)_2$ were found to be part of the catalyst structure. SEM micrographs demonstrated that the uncalcined ostrich had an amorphous crystal structure, while a hexagonal crystal structure was formed after calcination at 900 °C due to the breakdown of carbonates and the formation of metal oxides. The results showed that the best catalyst (sample calcined at 900 °C for 4 h) obtained a FAME yield of 90.56%.

In contrast, agricultural residues contain different inorganic elements such as Ca, K, Mg, and Si (Adepoju et al. 2022). The combustion of these residues resulted in a reduction in the carbon and oxygen composition, generating ash. These ashes are rich in alkali metal oxides such as CaO, MgO, K_2O, and SiO_2, which can be used as basic catalysts in fatty acid transesterification processes (Adepoju et al. 2022). For instance, Sitepu et al. (2020) tested the biodiesel production using heterogeneous palm bunch ash (PBA) catalysts. PBA contained K_2O as the main component, which enabled a high conversion of 98.9% using a catalyst weight of 18%, an oil-to-methanol molar ratio of 1:15, stirring at 5000 rpm, room temperature, and 10 min of reaction. It was found that this process could save 67–87% reaction time and up to 98% of electricity consumption compared to other transesterification methods. Adepoju (2022) studied the transesterification of *Asimina triloba* using wood ash as a catalyst. This catalyst had a BET surface area of 441 m^2/g with a composition of 42.6% CaO, 12.2% K_2O, and 23.9% SiO_2. The catalyst was tested at 40 °C, 2.5 wt% catalyst, 6:1 of oil-to-ethanol molar ratio and 40 min. These authors obtained a FAME yield of 92.5%. The results also showed that the catalyst could be reused, but its performance degraded after eight reaction cycles.

Biochar, hydrochar, and activated carbon are carbon-based materials that exhibit high thermal and mechanical stabilities and tunable properties as supports for anchoring appropriate functional groups to obtain a competitive catalyst (Saidi et al. 2023). Therefore, these materials have been explored in various studies to obtain novel catalysts for biodiesel production. Recently, Abdullah et al. (2022) synthesized a nanosized activated carbon from empty fruit brunch waste via hydrothermal carbonization (HTC) to produce a bifunctional catalyst. HTC of the biomass waste was carried out at 200 °C for 24 h, and the hydrochar was activated with H_3PO_4 (20%). The solid was pyrolyzed at 600 °C, and the final activated carbon was functionalized with K_2CO_3 and $Cu(NO_3)_2$ and pyrolyzed at 600 °C for 3 h. This catalyst was used for simultaneous esterification and transesterification of WCO. The results revealed that this carbon-based support had a surface area of 4056 m^2/g, resulting from hydrolysis, dehydration decarboxylation, aromatization, and recondensation during HTC. The final catalysts exhibited a surface area lower than 500 m^2/g and crystalline structure, as revealed by the XRD diffractograms. FTIR spectra showed the attachment of metallic species (i.e., K and Cu) on the carbon surface. The reaction system to obtain the biodiesel derived from WCO achieved 96% conversion and the catalyst could be reused for 6 cycles to obtain a final conversion of 63%.

A sulfonated biochar-based magnetic catalyst was prepared by Saidi et al. (2023). The biochar was produced by rice husk pyrolysis at 700 °C for 3 h. It was mixed with KOH 1 M to remove the silica and increase the pore size. Magnetic functionalization was performed using $FeCl_3$ and different weight ratios of $ZnCl_2$ at 25 °C for 3 h, followed by pyrolysis at 600 °C for 2 h. Finally, the magnetic biochar was treated with concentrated H_2SO_4 or $ClSO_3H$ as a sulfonating agent to obtain covalent bonds of SO_3H (sulfonic groups). Catalytic performance was tested for the esterification of oleic acid. The effects of reaction conditions (e.g., time, catalyst concentration, methanol/oil ratio, and temperature) were analyzed using Central Composite Design (CCD) and Response Surface Methodology (RSM). Saturation magnetization measurements indicated that the magnetism increased with increasing $ZnCl_2$ concentration. FTIR spectra showed the presence of SO_3H group, while textural parameter analysis demonstrated that surface area increased with sulfonation and presented a mesoporous structure. The catalyst could be reused for 6 cycles with FAME yields of 97.52% in the first cycle and 80.64% in the sixth cycle, respectively.

Renewable diesel and bio-jet

Renewable diesel has become more attractive in the transportation sector and the development of catalysts for its production has increased (Hongloi et al. 2022). Different catalysts have been studied for improving the deoxygenation of fatty acids (Safa-Gamal et al. 2021). Specifically, noble metal catalysts (e.g., Pd, Pt, and Ru) have been reported, but they are expensive and unattractive at the industry level (Safa-Gamal et al. 2021). Therefore, biomass-derived catalysts have been proposed. Table 7 describes the use of biomass-derived catalysts in renewable diesel production.

For example, the coconut shell was utilized as a precursor of carbon-based catalysts containing Co and Ag for the deoxygenation of palm fatty acid distillate (PFAD) (Safa-Gamal et al. 2021). The catalyst was prepared via the pyrolysis of coconut shells at 700 °C with subsequent activation with H_3PO_4 to promote an acidic nature that favored the decarboxylation activity. Then, the Ag and Co nitrate salts were impregnated, and thermal treatment was carried out at 600 °C to degrade the nitrate precursors. Deoxygenation was performed by mixing 10 g of oil with 0.3 g of catalyst at 350 °C for 60 min. XRD patterns revealed that the high crystallinity was associated with several metallic phases present on the catalyst surface. The activated carbon used as a support displayed a surface area of 350 m^2/g, which was reduced to 790 m^2/g when the material was impregnated with Ag-Co (10–10 wt%). SEM micrographs showed a homogeneous metal dispersion on the catalyst surface. PFAD deoxygenation with the best catalyst ($Ag_{10\%}$-$Co_{10\%}$) resulted in 77% hydrocarbon yield, while 95% was achieved under the optimized reaction conditions.

The use of deoxygenation catalysts to produce green diesel is challenging owing to their deactivation during the process and over time. Mohammed et al. (2022) studied the stability of a catalyst prepared from apricot seeds, an agricultural waste, in the hydrothermal production of green diesel fuel from WCO. First, the apricot seeds were soaked in H_3PO_4 and pyrolyzed at 500 °C for 60 min to obtain activated carbon. The activated carbon was sonicated in the presence of HNO_3 for 2 h at 60 °C. $PdCl_2$ was used to modify the carbon surface via incipient wetness impregnation, and the solid was pyrolyzed at 650 °C to obtain the catalyst. Finally, the catalyst was coated with a nanofilm aluminum protective layer using the sol–gel method to prevent the fast deactivation of the catalyst.

Rodriguez et al. (2023) prepared two catalysts derived from a biochar obtained via the pyrolysis of rice husk or banana midrib at 700 °C. The biochars were then activated with 3 M KOH or 2 M HCl. The catalytic performance was evaluated for the cracking of waste motor oil. This oil was composed of C_{15}-C_{50} hydrocarbons. The cracking reaction was carried out in a batch reactor in the temperature range of 400–425 °C with 0.4 wt% of catalyst. The product exhibited a chemical composition similar to that of commercial diesel (C_{10}-C_{27}), with a conversion of 90% using KOH-rice husk char. It is noteworthy that acidic treatment diminished the catalytic properties of both biomass-derived chars owing to the release of metallic species. Conversely, the basic catalysts achieved high conversions. Both treatments increased the surface areas being more evident for banana midrib char, which was confirmed by SEM micrographs that showed more cavities in the alkaline chars. XRD patterns showed that KOH activation removed silica from the rice husk char and enhanced the degree of carbon order in both chars.

The complex reactions to produce bio-jet involve the use of catalysts to address the selectivity and yield parameters. The use of noble metals such as Pt or Gd allows hydrogen transfer reaction to produce aromatic compounds in the bio-jet. Zeolites or alumina are commonly used as catalysts or catalytic supports, but they show poor adaptability for different biomass feedstock, excess cracking of molecules, high cost, and deactivation, which hinder the corresponding process scaling (Kannapu et al. 2022). Therefore, the search for alternative catalysts is mandatory, and biomass-derived catalysts are promising alternatives for addressing these drawbacks. Table 8 describes different studies related to the use of biomass-derived catalysts to produce bio-jet.

Ravindran et al. (2022) evaluated the conversion of palm kernel oil using a modified carbon-based catalyst prepared from bamboo (FeMo/ACB) via microwave heating. First, the support was obtained via bamboo pyrolysis at 600 °C. The biochar was then modified with KOH and pyrolyzed at 800 °C to produce an activated carbon. Activated carbon was functionalized with Mo and Fe species via co-precipitation. The final solid was thermally treated at 530 °C. Palm kernel oil was converted into bio-jet fuel as an alternative to solve the "palm oil controversy." Catalytic deoxygenation of the oil was performed in a microwave reactor. Characterization studies revealed that the highly porous structure and active acidic O-containing groups of the catalyst were strongly correlated with the deoxygenation activity. The introduction

Table 7 Recent studies of biomass-derived catalysts to produce renewable diesel

Waste	Treatment	Conditions for catalyst preparation	Reaction conditions	Yield or Conversion, %	References
Coconut shell waste	Thermochemical	Pyrolysis: 700 °C, 4 h, N_2 Chemical activation: H_3PO_4 (150 °C, 12 h) Wet impregnation: $Co(NO_3)_2.6H_2O$ and $((NH_4)_6Mo_7O_{24}.4H_2O)$ metal solutions (CoxMoy, where x = 10 wt.% and y = 5, 10, 15, and 20 wt.%), mixed vigorously (room temperature, 6 h), dried (110 °C, 12 h) Thermal treatment: 550 °C, 4 h (N_2 atmosphere)	Semi-batch reactor, Deoxygenation: oil (palm fatty acid distillate), 3% of $Co_{(10wt.\%)}$-$Mo_{(10wt.\%)}$/activated carbon, 350 °C, 2 h, 50 mL/min N_2, 400 rpm	92	Gamal et al. (2020)
Coconut shell waste	Thermochemical	Pyrolysis: 5 g of biomass, 700 °C, 4 h, heating rate of 5 °C/ min, 10 mL/min N_2 Chemical activation: 100 mL H_3PO_4 (150 °C, overnight) Wet impregnation: $Co(NO_3)_2$ and $AgNO_3$ metal solutions (CoxAgy, where $x = 10$ wt% and $y = 5$, 10, 15, and 20 wt%), and mixed vigorously (room temperature, 6 h), dried (110 °C, overnight) Thermal treatment: 600 °C, 4 h (N_2 atmosphere)	Semi-batch reactor, Deoxygenation: 10 g of oil (palm fatty acid distillate), 1% of $Co_{(10wt.\%)}$-$Ag_{(10wt.\%)}$/activated carbon, 350 °C, 2 h, 20 mL/min N_2	92	Safa-Gamal et al. (2021)
Macauba endocarp	Thermochemical	Carbonization: 550 °C, 2 h, 100 mL/min N_2, heating rate of100 °C/min Activation: 850 °C, 7 h, 200 mL/min CO_2, heating rate of 10 °C/min Wet impregnation: $Co(NO_3)_2$ to produce catalysts with 10 wt% of Co	Batch reactor, 350 °C, 3 h, 3 MPa H_2, 10% of Co/endocarp activated carbon, 300 rpm	97	Moreira et al. (2020)

of metallic species favored the bio-jet selectivity by 80%. Authors indicated that this catalyst could be used over 5 consecutive cycles.

Kannapu et al. (2022) prepared a MgO-activated carbon derived from rice husk for the bio-jet fuel production from pyrolysis of sawdust. Rice husks were pyrolyzed at 500 °C and subsequently modified with KOH solution. The biochar was then calcined at 750 °C. MgO was incorporated via impregnation with its nitrate salt. Finally, the solid was again calcined at 600 °C. Fast pyrolysis of sawdust was performed in a micropyrolyzer at 400–600 °C. Rice husks showed a poor surface area of 2 m^2/g, while activated carbon exhibited a high surface area of 775 m^2/g that diminished after metal impregnation. XRD diffractograms demonstrated that the

Table 8 Recent studies of biomass-derived catalysts to produce bio-jet

Waste	Treatment	Conditions for catalyst preparation	Reaction conditions	Yield or Conversion, %	References
Palm male flowers	Thermochemical	Pre-carbonization: 500 °C, 100 mL/min N_2 Palm male flowers carbonized with $Co(NO_3)_2$, 600 °C, 2 h	360 °C, 4 h, 5 MPa	77	Kaewtrakulchai et al. (2020)
Corncob	Thermochemical	100 g of biomass, 100 mL H_3PO_4 85%, 24 h, drying 100 mL $Fe(NO_3)_2$, 12 h, drying Pyrolysis: 1 h	500 °C, 50 mL/min N_2, catalyst/feedstock ratio: 1/1	54	Lin et al. (2020)
Corncob	Thermochemical	56.5% H_3PO_4 for 24 h 450 °C, 0.5 h, Microwave power of 700 W 10 g carbon, 96% H_2SO_4, 101.2 °C, 8.1 h	500 °C, 15 min, 160–170 mL/min N_2, 3 g of catalyst	8	Mateo et al. (2020)
Macauba endocarp	Thermochemical	Carbonization: 550 °C, 2 h, 100 mL/min N_2, heating rate of 100 °C/min Activation: 850 °C, 7 h, 200 mL/min CO_2 Modification: $Co(NO_3)_2$	350 °C, 4 h, 3 MPa H_2	98	Moreira et al. (2020)
Bamboo	Thermochemical	Carbonization: 600 °C, 0.5 h, 150 mL/min Ar Modification: KOH (85%), weight ratio: 1/1, 12 h Activation: 800 °C, 1 h (Ar atmosphere) Fe^{3+}, Fe^{2+} and Mo salts, 80% carbon, 530 °C, 2 h (N_2 atmosphere)	250 °C, 0.5 h, 5% of catalyst, microwave system	80	Ravindran et al. (2022)
Rice husk	Thermochemical	Biochar preparation Pyrolysis: 550 °C, 1 h, 75 mL/min N_2 Modification: biochar/KOH weight ratio: 3/1, drying: 110 °C, 12 h Activated biochar preparation Activation: calcination (750 °C, 1 h, N_2 atmosphere), modification (100 mL of 5 M HCl, 0.5 h, continuous stirred), drying: 110 °C, 12 h MgO/Activated carbon preparation Modification: $Mg(NO_3)$, dried (110 °C, 12 h) Calcination: 650 °C, 3 h, 100 mL/min N_2	1 mg of sawdust, 10 mg of catalyst (MgO/activated carbon), 600 °C	29	Kannapu et al. (2022)

organic crystalline structure of biochar changed to a microcrystalline carbon structure due to fine graphitization during calcination. SEM micrographs revealed a smooth rice husk surface that changed to a surface with cavities due to the several treatments applied. The main compounds produced from sawdust consisted of hepta-3,5-dien-2-one, ethylbenzene, p-xylene, and 1,4-dimethylbenzene, which are characteristic of bio-jet, demonstrating its effectiveness with a 29% yield. In contrast, the use of biochar, activated carbon, and other intermediate materials produced chemical compounds that were unsuitable for their use as bio-jets. This set of studies showed that there is a great opportunity to explore the preparation of heterogeneous catalysts derived from biomass waste to produce renewable diesel. Currently, research in this field has focused on the reaction process or biomass feedstock to produce biofuel using high-cost catalysts.

Bioalcohols

A pretreatment stage for converting cellulose into simple sugars is required before bioalcohol production (Gohain et al. 2021). Recent advancements in biomass pretreatment and hydrolysis using biomass-derived heterogeneous catalysts have overcome the environmental and economic limitations of homogeneous catalysts (Gohain et al. 2021). This technology is crucial for the conversion of lignocellulosic biomass into biofuels and value-added chemicals (Higai et al. 2021). However, traditional solid acids contain single functional groups, which do not exhibit efficient catalytic properties (Lu et al. 2021). For example, polymers with Brønsted acids (e.g., commercial amberlyst, nafion, and sac) cannot adsorb lignocellulose, resulting in a low hydrolysis yield. Oxide catalysts (e.g., zeolites, niobic acid, and SiO_2-Al_2O_3) are good adsorbents; however, they cannot depolymerize lignocellulose (Lu et al. 2021; Prabhu et al. 2021). Therefore, the development of biomass-derived catalysts with tailored properties has attracted significant attention. For illustration, Table 9 shows the application of waste biomass to prepare catalysts to produce bioethanol and biobutanol.

For example, Si et al. (2017) evaluated the hydrolysis of bamboo biomass using two surfactants for biofuel production. Surfactants can emulsify and dissolve extractives contained in wood structures, and their synergistic effect with ionic liquids (ILs) was also studied. A sulfonated cross-linked chitosan acid catalyst was synthesized and used in the reaction. Hydrolysis was performed by mixing 1-Butyl-3-methylimidazolium chloride ([BMIC]Cl), the prepared catalyst, and a surfactant (Tween 80, polyethylene glycol, and sodium dodecyl sulfate) in a round-bottom flask. The results showed that the catalyst improved the reduction in total sugars, achieving yields ranging from 3% (without catalyst) to 86% (1:20 bamboo to catalyst). The use of surfactants enhanced the hydrolysis in the following order: Tween (12%) > SDS (10%) > PEG (7%). The catalyst was reused for 4 cycles with a suitable sugar yield of 80%. SEM micrographs showed that the catalyst was spherical with a porous structure and folded meandering surface.

Chen et al. (2019) prepared an acid catalyst using rice husk as a precursor with one-step carbonization and sulfonation and its subsequent application for the hydrolysis and saccharification of corncob. The one-step procedure is advantageous because of its simple operation, shorter reaction time, and lower energy consumption than the two-step method. Rice husks were mixed with H_2SO_4 (96%) in a hydrothermal synthesis reactor at 160 °C for 6 h. The analysis demonstrated that this catalyst consisted of aromatic carbon sheet structures with –SO_3H, –COOH, and –OH groups. In the corn cob hydrolysis and saccharification, this catalyst showed a maximum reducing sugar yield of 486.53 mg/g and xylose of 253.03 mg/g, being twofold and fivefold higher than that of control, respectively.

Gohain et al. (2021) studied the hydrolysis capacity of biomass-derived catalysts prepared from *Musa balbisiana* colla peel (BPA), water hyacinth (WH), Carica papaya stem (CPS), *Tectona grandis* leaves (TGL), and de-oiled *Rhodotorula mucilaginosa* biomass (RCA). The first four biomass samples were calcined, and the de-oiled biomass was transformed into potassium-impregnated activated carbon. Bioethanol was produced from de-oiled *Scenedesmus obliquus* microalgae, in which catalysts were used in the saccharification step. Alkaline saccharification was performed using 2 wt% of the catalyst. The solid–liquid mixture was maintained at a 1:10 ratio and then autoclaved at 121 °C for 20 min. The hydrolysate was fermented and the catalyst efficiency in saccharification followed the trend: CPS (60%) > BPA (50%) > RAC (49%) = WH > TGL (42%). The catalysts exhibited high basicity, with K being the main element in the form of K_2O and K_2CO_3. The ethanol yield after fermentation was in the range of 45.03–68.32%.

Higai et al. (2021) obtained an activated carbon-based catalyst derived from coconut shells for its use in saccharification. Specifically, an acid catalyst was prepared by immersing the coconut shell in a phosphoric acid solution at 25 °C for 1 h. The mixture was then heated at 170 °C for 2 h to remove water. Subsequently, the mixture was heated to 400–600 °C for 1 h under air atmosphere, rinsed with hot distilled water, and dried. The activated carbon was sulfonated with fuming or chlorosulfuric acid to obtain –SO_3H active sites. Acid saccharification was performed by mixing 0.5 g of the catalyst (1 g with microcrystalline cellulose and 30 g) in an autoclave at 180 °C. Catalyst characterization showed that the activated carbon modified with chlorosulfuric acid had the lowest surface area (659 m^2/g), while the sulfonated catalysts exhibited surface areas of approximately 1057–1381 m^2/g. XPS analysis revealed that all catalysts contained 46–58% oxygenated species in their structures.

Table 9 Recent studies of biomass-derived catalysts to produce bioalcohols

Waste	Treatment	Conditions for catalyst preparation	Operational conditions	Concentration	References
Glucose	Thermal	Carbonization hydrothermal: 180 °C, 4 h, glucose (5 g), citric acid (2.5 g), hydroxyethylsulfonic (1.5 g), deionized water (40 mL) Washing: methanol and deionized water Drying: 80 °C, 8 h	0.4 g of catalyst, 0.8 g of cornstarch, 40 mL distilled water, 150 °C, 3 h	Total sugar: 7 g/mL	Nata et al. (2015)
Rice straw	Thermochemical	15 g of biomass, 120 mL 6% KOH, 120 °C, 4 h Solid pyrolyzed under N_2, 400 °C, 1 h, followed by 600 °C for 2 h Chemical activation: 20 mL concentrated H_2SO_4, 150 °C, 10 h under N_2	0.05 g rice straw (pretreated with KOH), 0.05 g water, 0.05 g of catalyst, 140 °C, 2 h	Total sugar: 63%	Bai et al. (2016)
Chitosan	Chemical	2 g chitosan, dripping of 2.5 mL H_2SO_4 (98%), 5 h	4 g 1-Butyl-3-methylimidazolium chloride, 0.1 g bamboo, 0.1 g of catalyst, 120 °C, 24 h, 20 rpm	Total sugar: 68%	Si et al. (2017)
Rice husk	Thermochemical	Hydrothermal synthesis: H_2SO_4 (96%), 160 °C, 6 h. Washing: with hot water to remove excess H_2SO_4 and neutral pH. Drying: 105 °C, 24 h	0.5 g corncob, 160 °C, 3 h, 0.5 g/g of catalyst	Total sugar: 487 mg/g	Chen et al. (2019)
Tectona grandis leaves	Thermal	Calcination: 700 °C, 4 h	Catalytic hydrolysis: 121 °C, 0.5 h Fermentation: *Saccharomyces cerevisiae,* 32 °C	Total sugar: 68% Ethanol: 8 g/L	Gohain et al. (2021)
Coconut shells	Thermochemical	10 g of biomass, H_3PO_4, 25 °C, 1 h 400 °C, 1 h under a flow of air Activation: 10 mL H_2SO_4, 1 g carbon, 10 h, 80 °C	0.5 g of catalyst, 1 g of microcrystalline cellulose, 180 °C, 1 h	Total sugar: 39%	Higai et al. (2021)
Microcrystalline cellulose	Thermochemical	10 g of microcrystalline cellulose, 1 L (10 mmol/L) of $FeCl_3$, 400 rpm, 100 °C, 5 h. Drying: 105 °C overnight Carbonization: 350 °C, 1 h, N_2 Sulfonation (H_2SO_4): 98% w/w, solid/liquid ratio: 1/10, 130 °C, 10 h Washing: hot water (< 80 °C) Drying: 105 °C overnight	Ratio of sugarcane bagasse/catalyst/water: 1/1/22 (g/g/mL), 170 °C, 10 min	Xylose: 91.62%	Lu et al. (2021)

The catalysts obtained at 400 °C and modified with chlorosulfuric acid showed the highest conversion (75%) of monosaccharides when the preparation conditions were optimized.

Bio-oil

The yield of hydrocarbons and the absence of oxygen-containing compounds (e.g., carboxylic acids or alcohols) in the bio-oil structure are important characteristics associated with their quality because they increase the corrosive capacity, acidity and viscosity of bio-oil and decrease its calorific value (Rabiu et al. 2018). These limitations can be overcome by using a suitable catalyst during pyrolysis or hydrothermal liquefaction of biomass to obtain biofuel (Kumar et al. 2019).

Several studies have focused on obtaining bio-oil using zeolite-based catalysts, with HZSM-5 being the most popular catalytic material (Bhoi et al. 2020) because it has acidic sites that allow high hydrocarbon yields (Zhao et al. 2019). However, the main disadvantage of this catalyst is the low possibility of reuse because, after the first reaction, it is deactivated because of its microporous structure and acidic nature, which favors the deposition of coke on its surface (Crespo et al. 2023). With the aim of using green and low-cost catalysts, some studies have reported the preparation of heterogeneous catalysts from waste biomass, see Table 10.

The incorporation of metals in the preparation of the catalysts enables the generation of a significant number of active (metallic) sites, which helps in the production of bio-oil with a low content of water and oxygenated compounds because it favors the deoxygenation reaction (Kopperi and Mohan 2023). This eliminates the extra step used when the product contains compounds that are not of interest, thus obtaining refined biofuels (Du et al. 2022).

Dai et al. (2019) used rice husk derived biochar obtained via microwave-assisted pyrolysis at 550 °C. This biochar was modified with Fe using iron nitrate as the precursor salt and then calcined at 600 °C for 1 h. The catalyst was evaluated in the pyrolysis of torrefied corn cob to obtain a bio-oil yield of up to 36.55 wt% (42.78 wt% without a catalyst), where the gas yield increased with the catalytic system. However, the use of a catalyst enhanced the yield and selectivity of phenol and cresol. SEM micrographs showed cavities on the catalyst surface due to the pyrolysis treatment, where biochar exhibited a low area (4.17 m^2/g), whereas the catalyst achieved 110 m^2/g. NH_3-TPD (i.e., ammonia temperature-programmed desorption) tests demonstrated the acidic nature of this catalyst. A similar yield (33.2%) was obtained with a catalyst prepared by impregnation of Fe from a carbon-based catalyst derived from pine wood sawdust via pyrolysis at 600 °C (Liu et al. 2022).

Biswas et al. (2021) prepared a Ni-impregnated material. This catalyst was obtained from the biochar derived from rice straw via pyrolysis at 450 °C. Subsequent activation with 3 M KOH and thermal treatment at 700 °C under N_2 flow were performed, and Ni impregnation was performed for subsequent thermal treatment at 700 °C. This catalyst was used to obtain bio-oil by the hydrothermal liquefaction of alkaline lignin, which resulted in a high yield (72 wt%) in which diverse phenolic compounds, such as phenols, aliphatic ketones, and aromatic hydrocarbons, were identified. The activated carbon (without supported metal) exhibited a surface area of 640 m^2/g, while the area of the Ni-catalyst was reduced to 564 m^2/g because of the metal filling the activated carbon lattice. NH_3-TPD analysis showed that Ni increased the acidity of activated carbon. The XRD diffractograms confirmed the presence of the metallic species.

Zeng et al. (2021) developed an economical and easy-to-recover catalyst from *Choerospondias axillaris* seeds for the microwave-assisted catalytic pyrolysis of corn cobs to produce phenol-rich oil. The seed powder was modified with H_3PO_4 and microwave pyrolysis was performed at 600 °C to produce activated carbon. This material was impregnated with 0.1 M $Fe(NO_3)_3$ under ultrasonication for 40 min to achieve uniform incorporation of Fe. The dried sample was carbonized at 600 °C for 1 h to obtain the magnetic catalyst. BET analysis revealed that the biochar had a surface area of 45 m^2/g, while the catalysts showed a surface area of 592–732 m^2/g. SEM images indicated a catalyst with cavities and pores due to the treatments used. The main chemical components of the corncob-derived oil were simple phenolic compounds, followed by aldehydes and furan compounds. The catalyst was still selective for phenolic compounds after 5 cycles of reuse.

Corn cob was used to prepare a catalyst based on activated carbon through carbonization (500 °C for 1 h) and subsequent impregnation with Ni in the form of monoxide (Li et al. 2023). This catalyst was evaluated in the pyrolysis of WCO (in a fixed-bed reactor), obtaining a yield of up to 59.64 wt%. Catalyst characterization revealed the acidic nature of the surface via NH_3-TPD. This property is crucial to this reaction system. Brunauer–Emmett–Teller (BET) analysis showed that the catalyst had micro- and mesopores and a surface area of approximately 720 m^2/g. An increase in nickel (10%) loading on the catalyst was favorable for improving the bio-oil yield and monocyclic aromatic hydrocarbon selectivity. The bio-oil products were classified as gasoline (C_5-C_{12}), diesel (C_{10}-C_{18}) and jet fuel (C_8-C_{16} alkanes and aromatics).

Carbon-based catalysts are not the only effective materials that can be prepared from residual biomass, because wastes that contain large amounts of other interesting catalytic compounds can also be used. For example, Arun et al. (2020) obtained calcium hydroxide from clam shells to obtain bio-oil from *Scenedesmus obliquus* microalgae via hydrothermal liquefaction. The catalysts were prepared by calcination at 800 °C for 2 h. The powder was mixed with 2N HCl and 2

Table 10 Recent studies of biomass-derived catalysts to produce bio-oil

Waste	Pretreatment	Conditions for catalyst preparation	Operational conditions for bio-oil production	Concentration, wt%	References
Moso bamboo	Thermal	Pyrolysis: 700 °C, 20 min, 0.15 m^3/min N_2, microwave power of 700 W	Microwave-assisted catalytic pyrolysis: biomass: 50 g, 700 °C, 20 min, 0.15 m^3/min N_2, 20% of catalyst, microwave power of 600 W	41	Dong et al. (2018)
Rice husk	Thermochemical	Pyrolysis: 550 °C Washing: water, 60 °C, 6 h. HCl 0.1 M, 4 h, 100 mL iron nitrate, under ultrasonic processing (40 min) Fe/biochar was calcined (600 °C, 1 h)	Microwave-assisted catalytic pyrolysis: 10 g torrefied corn cob, 30 g of SiC, 10 g of catalyst, 500 °C, 20 min	34	Dai et al. (2019)
Clam shells	Thermochemical	Calcination: 800 °C, 2 h $Ca(OH)_2$ precipitation: 37 g of calcined powder, 2N HCl, 2N NaOH (0.5 h, room temperature)	Hydrothermal liquefaction: microalgae biomass (*Scenedesmus obliquus*), 300 °C, 1 h, 0.6% of catalyst	40	Arun et al. (2020)
Rice husk	Thermochemical	Pyrolysis: Fixed bed reactor, 450 °C. activation: 3 M KOH, 3 h, room temperature Calcination: 700 °C, 3 h, N_2 Co-impregnation: 10% Ni ($Ni(NO_3)_2$), 3 h	Hydrothermal liquefaction: 280 °C, 10 g of alkali lignin, 10% of catalyst	72	Biswas et al. (2021)
Tea waste	Thermochemical	Activation: KOH (85%), room temperature 500 °C, 2 h, 120 mL/min N_2	Pyrolysis: 2 g biomass, 500 °C, 0.33 g of catalyst	41	Tahir et al. (2021)
Peanut shell	Thermochemical	Pyrolysis by microwave: 30 g of biomass, 550 °C, 0.25 h Modification: $FeCl_2$, ammonia and $FeCl_3$, 50 °C, 0.5 h	Rapid pyrolysis: peanut shell, 550 °C, 18 s, 10% of catalyst (Fe/Carbon)	38	Bu et al. (2022)
Pine wood	Thermochemical	Pyrolysis: 800 °C, 1 h, N_2 Activation: 800 °C, 1 h, CO_2 Modification: 10% $Fe(NO_3)_3$, 400 °C, 2 h, 200 mL/min N_2	Pyrolysis in a fixed bed reactor. Pine sawdust, 600 °C, 10 min	33	Liu et al. (2022)
Corn cob	Thermochemical	Activation: 90 g of dried corn cobs and H_3PO_4 at room temperature, 10 h. Drying: 105 °C Carbonization: 30 g mixture prepared, 500 °C, 1 h Modification: Ni, 10 g of char, 45 °C, 6 h Calcination: 500 °C, 0.5 h	Pyrolysis: fixed-bed reactor, 600 °C, 0.25 h, 3 mL of waste cooking oil, 10% of catalyst (Ni/Carbon)	60	Li et al. (2023)

N NaOH, and $Ca(OH)_2$ was precipitated and recovered. This catalyst showed a surface area of 42 m^2/g and agglomerated morphology, as determined by SEM. The reaction achieved a bio-oil yield of 39.6 wt% consisting mainly of hydrocarbons, esters, and oxyacids.

Techno-economic analysis of liquid biofuel production

Techno-economic analysis (TEA) is fundamental for estimating the capital cost, operating cost, mass balance, and energy balance for process design and simulation (Rajendran et al. 2022). This analysis allows industries to determine the viability of their processes and systems and identify areas for improvement (Saetiao et al. 2023). TEA of biofuel production is fundamental to develop both economic and sustainable supply chain. For example, the commercial feasibility of using camelina seed oil to produce bio-jet in a rural location in Canadian Prairies was studied by Li et al. (2018a). The base case scenario involved the processing of 252,000 tons/year of camelina oil. To model the cost of camelina oil, the logistic cost of feedstock (collection, transport, and storage) was considered. An economic engineering model was proposed using SuperPro Designer®. This model focused on the capital investment, scalability, and viability of producing bio-jet and other high-value co-products based on biorefineries with capacities of 112.5–675 million L/year. The results revealed that the selling price of biofuel ranged from \$0.40 to \$1.71 per L, depending on variations in the plant capacity and feedstock cost. The marginal and mean cost curves indicated that the Canadian region could handle a plant capacity of up to 675 million L/year with a capital investment of \$167 million.

Kang et al. (2019) evaluated *Miscanthus sacchariflorus* as a feedstock for bioethanol production and its viability on an industrial scale. The experimental data obtained in the small-scale process were also compiled to perform the sensitivity and economic analyses. The results showed that a plant with 606,061 tons/year of *Miscanthus sacchariflorus* could reach a production of 1×10^9 L of bioethanol as the main product, with a total production cost of \$1.76 per L. The co-products (lignin and xylose molasses) could be sold or incorporated into the process as a source of heat, providing the process of added profitability and achieving a reduction in the final cost of bioethanol production (\$1.31 per L). One of the factors directly influencing bioethanol production costs was the high cost of the enzymes (\$0.328/L).

Martinez-Hernandez et al. (2019) conducted simulation studies and TEA using vegetable oil as feedstock to produce renewable diesel and bio-jet. They carried out hydrodeoxygenation of vegetable oil to produce renewable diesel and propane as co-product, while hydrodeoxygenation and isomerization/hydrocracking were used to obtain bio-jet as the main product and other products (i.e., green diesel, naphtha, and propane). The simulation and TEA analyses were developed in SuperPro Designer®, linked to Excel Visual Basic to perform Monte Carlo simulations and obtain a better estimation of the minimum selling price (MSP). The results demonstrated that a green diesel plant with an annual production capacity of 63,000 barrels/year can be a viable and profitable option with a minimum selling price of \$1/L, while a bio-jet plant with a production capacity of 75,000 barrels/year can obtain a minimum selling price of \$1.35/L.

A techno-economic study on the potential of three Canadian forest biomass feedstocks (spruce, corn stover, and wheat straw) to produce renewable diesel via pyrolysis and hydroprocessing in a model plant with a capacity of 2,000 tons per day was carried out by Patel et al. (2019). Fast pyrolysis was performed in a fluidized bed reactor at 400–550 °C. Aspen Plus® was used to model the process, where the use of grinders, dryers, screen separators, reactors, cyclone separator units, condensers, hydroprocessing units, pumps, and storage tanks was considered in the techno-economic analysis. H_2 production was analyzed because this gas is fundamental in the hydroprocessing of bio-oil to be upgraded to renewable diesel. The highest bio-oil yield (65%) was obtained for spruce, followed by corn stover (55%) and wheat straw (49%). The low yield of wheat straw was due to its low carbon content. In the techno-economic analysis, the cost of renewable diesel from spruce was \$0.98/L with H_2 purchased and \$1.06/L when it was produced. The prices were \$1.14/L and \$1.22/L for corn stover and wheat straw, respectively, with H_2 production. It is noteworthy that the fossil fuel price is \$0.42/L and 1.59 \$/L for diesel (OPEC 2023).

Among forest residues, eucalyptus in Brazil is considered a strong candidate for bio-oil production because of its abundance and wide availability with approximately 5.7 million hectares planted (IBÁ 2019). It is estimated that 243,000 tons of eucalyptus residue are generated annually in Sao Paolo and can be used as feedstock to produce approximately 61 million L/year of bio-oil via fast pyrolysis (Iglesias et al. 2021). In this context, Pighinelli et al. (2018) took as a basis for their simulation a production capacity of 2000 tons/day of *Eucalyptus benthamii* obtaining a minimum selling price of \$28/GJ and a high calorific value of 30.76 MJ/kg. van Schalkwyk et al. (2020) evaluated the minimum selling price of bio-oil via a TEA, considering an internal rate of return (IRR) of 10%. On the other hand, Pinheiro et al. (2019) reported that bio-oil production costs varied in the range of \$6–51/GJ. According to the TEA conducted by Iglesias et al. (2021), the new generation of biorefineries could reach a processing capacity of 60,000 to 5,000 tons/

year of eucalyptus residues, with a minimum selling price ranging from \$11.6 to \$19.3/GJ.

Barbera et al. (2020) focused on the production of bio-jet from WCO, performing a comparative study between two methods: catalytic transfer hydrogenation (CTH) with isopropanol as hydrogen donor and conventional hydrogenation (CH). TEA was performed based on a process simulation with Aspen Plus® software. For both processes, a plant-processing capacity of 1000 tons/day of WCO was set. Reagent costs (WCO \$0.15/kg, hydrogen \$1.6/kg, and isopropanol \$1.30/kg) were estimated according to the literature. The total plant capital expenditures for the CTH and CH processes were \$7.3 million and \$149.7 million, respectively. The revenues obtained for liquid biofuels (bio-jet, diesel, naphtha, and kerosene) by both methods are similar, at approximately \$140.4 million (CTH) and \$141.4 million (CH). To be economically profitable, the bio-jet obtained via CTH and CH must be sold at \$0.79/L and \$0.44/L, respectively. The selling price of the bio-jet obtained with CTH was higher than that obtained with CH, mainly because of the high cost of isopropanol, which represents up to 68% of the manufacturing cost.

Hsu et al. (2021) evaluated the impact of the WCO hydro-conversion to bio-jet and its large-scale application whit processes with one, two or three stages. They found that with a plant-processing capacity of 300 tons/day of oil, the three-stage process was the most appropriate, with a total capital investment of \$17.24 million and a low minimum selling price for bio-jet of \$0.31/L based on the price of WCO (\$0.63/kg) with a probability of profitability of 11.94%. Moreover, the 3-stage hydro-processed bio-jet process achieved a maximum yield of 57 wt%.

The optimization of WF oil extraction using solvents and its conversion to biodiesel via TEA was performed by Rajendran et al. (2022). Under the optimized reaction conditions, a maximum FAME conversion of 96.3% was achieved. The TEA simulation considered a plant-processing capacity of 10 MT/h. The raw material costs of the biochar catalyst (\$1/kg), ethanol (\$0.75/kg), FW (\$0/kg), and methanol (\$0.24/kg), and biodiesel (\$0.84/kg) were considered. Results displayed that the TCP was \$33.73 million with annual revenues of \$24.14 million for a useful life of the plant of 20 years and an investment recovery rate of 3.16 years and minimum selling price of \$0.46/kg. The annual biodiesel and crude glycerol production was 22,710.4 MT and 3315.08 MT, respectively, with 37.11 MJ of energy required to produce 1 kg of biodiesel.

One of the main problems facing olive oil production is the generation of a large volume of olive mill wastewater (OMW), which pollutes the environment. Therefore, Khan et al. (2022) conducted a TEA for bio-oil recovery from OMW sludge via catalytic pyrolysis using different types of cooling schemes and a plant capacity of 93 ton/day of dry biomass (Fig. 9). The performance of the model with a vapor compression refrigeration machine in scheme 1 (Fig. 9a) was evaluated and compared with that of the model with an absorption refrigeration machine in scheme 2 (Fig. 9b). Both schemes were modeled using Aspen Plus®. The results showed that the bio-oil production cost obtained by schemes 1 and 2 ranged from €2.16–6.19/GGE (gasoline gallon equivalent) and €1.78–5.01/GGE, respectively. It is worth mentioning that a basis of capital investment of €22.1 million and operating expenses of €4.6 million were considered for scheme 1, while for scheme 2, the capital and operating costs were 17.5 and 3.6 million euros, respectively. From an energy and economical point of view, it was observed that scheme 2 showed a higher energy efficiency (0.7%) and better economic performance (minimum selling price = €2.74/GGE) than scheme 1. The results obtained were competitive and favorable, revalidating the possibility of bio-oil production via fast catalytic pyrolysis on an industrial scale.

Saetiao et al. (2023) utilized with Aspen Plus® to design a small-scale biodiesel plant with a production capacity of 10,000 tons per year using commercial-grade pure triolein, achieving a biodiesel purity of 99.99% and considering a projected plant lifetime of 20 years. As the prices of reagents and products may fluctuate, and the estimations change, therefore authors considered a range of prices for methanol (\$0.13-\$0.42 per kg), triolein (\$0.195-\$0.280 per kg) and biodiesel (\$0.90–\$1.15 per kg). The analysis showed that the total production cost (TPC) was estimated to be 4,169,698 USD, where raw materials had the highest cost (65.51%), followed by utilities (11%), and labor costs (5.46%). The net present value (NPV) of \$415 million demonstrated that the project was economically viable with a low loss risk. The payback period for recovering the investment was 7.17 years. Authors concluded that changes in raw materials and product costs could have a significant impact on the project feasibility.

Omidkar et al. (2023) tested a new catalytic process in the presence of methane to produce green diesel from WCO. Due to the relevance and expectation of the process, TEA and life cycle analysis were performed. The results were comparable to those of other conventional and commercial methods reported in the literature. This promising method was able to reduce energy consumption (0.93 kW/kg green diesel) and production costs (\$0.365/kg) compared to other commercial methods such as hydrotreatment (\$0.574/kg) and alkali-catalyzed process (\$0.513/kg). Also, the life cycle analysis showed that the process was environmentally friendly and could reduce the emissions of polluting gases (CO_2). From an economic perspective, the process is profitable because the minimum selling price is lower than the current price of conventional fuels in the market.

As can be seen, the TEA tool provides relevant information about the economic feasibility of a process, and it depends on a variety of factors that, if not managed

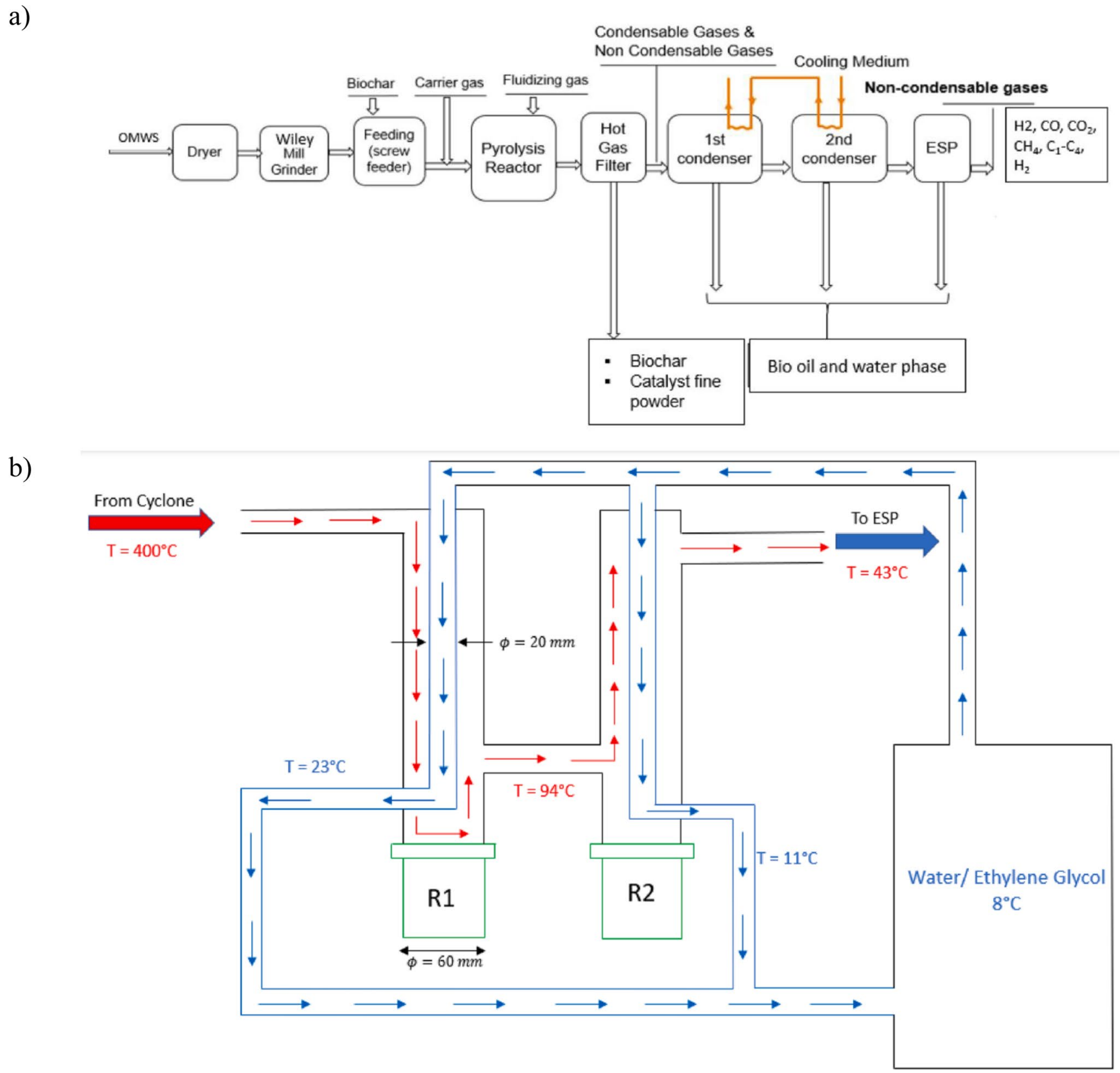


Fig. 9 Bio-oil from oil mill wastewater sludge via catalytic pyrolysis using different two cooling schemes: **a** vapor compression refrigeration machine and **b** absorption refrigeration machine (Khan et al. 2022). *ESP* Electrostatic precipitator, *OMWS* Olive mill wastewater sludge, *R1, R2* condensers

properly, make the product unprofitable in the market. It is evident that the production cost of biofuels is still highly dependent on the cost of raw materials. Therefore, the search for abundant, suitable, low-cost raw materials such as residual biomass is fundamental.

Future remarks and perspectives

In the context of a future world economy based on liquid biofuels, more attempts should be made to guarantee low-carbon transition. By integrating biofuels into the existing transportation and industrial infrastructure, low-income countries can reduce their reliance on imported oil and create a more sustainable and resilient energy system. Governments worldwide must implement policies and regulations to encourage the production and use of different biofuels. Incentives, including tax credits, subsidies, and renewable energy mandates, would help to create a favorable market environment for biofuel producers, leading to increased investment and growth in the sector, especially in developed countries.

The future scope of biofuels derived from waste biomass is therefore promising. However, research, development, and collaboration among academia, industry, and governments are crucial for achieving the full potential of biofuels derived from waste biomass and integrating them into the global energy system. Several challenges must be addressed to ensure its successful implementation and widespread adoption. The availability and sustainability of biomass feedstock pose a significant challenge. The scaling up biofuel production requires a consistent and abundant supply of biomass without negatively affecting food production, land-use, water resources, or biodiversity. It is also important to improve and optimize biomass conversion technologies, increase their efficiency, and reduce costs. The development of improved biochemical and thermochemical methods can lead to higher yields, better energy efficiency, and lower greenhouse gas emissions. The advancements in catalysts, enzymes, and pretreatment techniques will play a vital role in improving the overall efficiency of biofuel production.

On the other hand, there is a critical need for innovative catalyst development to enhance the catalytic conversion of biomass-derived intermediates into biofuels. Solid catalysts, in particular, present opportunities for improved selectivity, durability, and recyclability compared to their liquid counterparts. Future research should research into the design and synthesis of novel solid catalyst materials with tailored properties, exploring catalytic mechanisms and optimizing reaction conditions for maximum biofuel production.

Furthermore, the integration of artificial intelligence and machine learning techniques into biomass-to-biofuel processes can offer predictive modeling and optimization capabilities. These technologies can help researchers identify optimal conditions, predict yield outcomes, and design efficient catalytic systems. By taking advantage of data-driven approaches, future studies can accelerate the development and implementation of biomass waste conversion technologies.

Lastly, a comprehensive life cycle assessment is essential to evaluate the environmental sustainability and overall impact of biomass-to-biofuel processes. Future research should address the ecological footprint, energy balance, and socioeconomic aspects associated with large-scale implementation, ensuring that biofuel production from biomass waste aligns with broader sustainability goals. Collaborative efforts between researchers, industry stakeholders, and policymakers will be crucial to navigating the complexities of scaling up biomass waste utilization for biofuel production while addressing economic, social, and environmental considerations.

In addition, it is important to point out that public perceptions and acceptance of biofuels can influence their adoption. The prevailing collective concerns related to land-use change, food security, water usage, and potential environmental impacts should be addressed and resolved. The implementation of effective communication with society and raising awareness about the benefits and sustainability of biofuels can help overcome misconceptions and gain public support. Continuous innovation, technological advancements, supportive policies, and public engagement are key parameters for unlocking the full potential of biomass-derived biofuels in the global economy. In this direction, the benefits of biomass, as a promising source of sustainable biofuels, should be highlighted. The diversity in feedstock options provides flexibility in biofuel production, making it adaptable to regional and local contexts.

The challenges and opportunities presented in this review underline the need for continued research and investment in the biofuel sector. The transition to sustainable and economically viable biofuels is not only a technological challenge, but also an environmental imperative.

Conclusions

Biofuels derived from waste biomass have attracted significant attention as promising alternatives to fossil fuels. Unlike the sources used to obtain the traditional fuels, the waste biomass is continuously generated making biofuels a long-term energy solution. They offer several advantages such as reduced greenhouse gas emissions, potential waste management solutions, and decreased reliance on nonrenewable resources.

The sustainability of biofuels production depends on the feedstock, reagents, processes, and technologies, which have different social, economic, environmental, and political impacts. The circular economy approach requires the large-scale economic production of biofuels based on an effective "waste-to-wealth" strategy. It is clear that a multidisciplinary approach is required to achieve zero-waste economy, and the society is still far from achieving this goal.

The ongoing research and current advances have focused on improving the biofuel production processes and optimizing the conversion efficiency of waste biomass. Advancements in biochemical and thermochemical conversion technologies such as fermentation, pyrolysis, and gasification are expected to enhance the economic viability and scalability of biofuel production. On the other hand, the synthesis of heterogeneous catalysts from biomass waste provides a more ecological and profitable route for biofuel synthesis. They have gained popularity for biofuel synthesis. They are low-cost and readily available when residual biomass is used as a support precursor, thus obtaining additional advantages over expensive catalysts based on only metallic elements. Therefore, it is vital to identify and valorize a wide spectrum of raw materials that can potentially be used as catalyst precursors. In this sense, carbon-based catalysts have shown an extraordinary ability to tailor their physicochemical properties, but also provide an inert surface and thermal stability, which are characteristics that offer advantages over other supports. Nevertheless, catalyst design is paramount from a green synthesis perspective to successfully achieve suitable biofuel conversion and selectivity. However, it is also important that these catalysts can be reused for several cycles with low deactivation. These challenges must be overcome to have the possibility of a high production yield.

In conclusion, the utilization of biomass waste as a raw source for biofuels and solid catalysts holds significant promise for addressing both environmental and energy challenges. By converting organic waste materials into biofuels, we can contribute to a more sustainable and renewable energy future, reducing dependence on finite fossil fuels.

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Declarations

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References

Abbaszaadeh A, Ghobadian B, Omidkhah MR, Najafi G (2012) Current biodiesel production technologies: a comparative review. Energy Convers Manage 63:138–148. https://doi.org/10.1016/j.enconman.2012.02.027

Abdelfattah MS, Abu-Elyazeed OA, Mawla EA, Abdelazeem, (2018) On biodiesels from castor raw oil using catalytic pyrolysis. Energy 143:950–960. https://doi.org/10.1016/j.energy.2017.09.095

Abdullah B, Muhammad SAFS, Shokravi Z, Ismail S, Kassim KA, Mahmood AN, Aziz MMA (2019) Fourth generation biofuel: a review on risks and mitigation strategies. Renew Sustain Energy Rev 107:37–50. https://doi.org/10.1016/j.rser.2019.02.018

Abdullah RF, Rashid U, Hazmi B, Ibrahim ML, Tsubota T, Alharthi FA (2022) Potential heterogeneous nano-catalyst via integrating hydrothermal carbonization for biodiesel production using waste cooking oil. Chemosphere 286:131913. https://doi.org/10.1016/j.chemosphere.2021.131913

Adepoju T, Victor E, Ekop E, Emberru R, Balogun T, Adeniyi A (2022) Residual wood ash powder: A predecessor for the synthesis of CaO-K_2O- SiO_2 base catalyst employed for the production of biodiesel from *Asimina triloba* oil seed. Case Stud Chem Environ Eng 2:100252. https://doi.org/10.1016/j.cscee.2022.100252

Adepoju T (2020) Optimization processes of biodiesel production from pig and neem (*Azadirachta indica a.Juss*) seeds blend oil using alternative catalysts from waste biomass. Ind Crops Prod 149:112334. https://doi.org/10.1016/j.indcrop.2020.112334

Ahmed HA, Altalhi AA, Elbanna SA, El-Saied HA, Farag AA, Negm NA, Mohamed EA (2022a) Effect of reaction parameters on catalytic pyrolysis of waste cooking oil for production of sustainable biodiesel and biojet by functionalized montmorillonite/chitosan nanocomposites. ACS Omega 7:4585–4594. https://doi.org/10.1021/acsomega.1c06518

Ahmed SF, Mofijur M, Chowdhury SN, Nahrin M, Rafa N, Chowdhury AT, Nuzhat S, Ong HC (2022b) Pathways of lignocellulosic biomass deconstruction for biofuel and value-added products production. Fuel 318:123618. https://doi.org/10.1016/j.fuel.2022.123618

Ahmed M, Ahmad KA, Vo DV, Yusuf M, Haq A, Abdullah A, Aslam M, Patle DS, Ahmad Z, Ahmad E, Athar M (2023) Recent trends in sustainable biodiesel production using heterogeneous nanocatalysts: Function of supports, promoters, synthesis techniques, reaction mechanism, and kinetics and thermodynamic studies. Energy Convers Manage 280:116821. https://doi.org/10.1016/j.enconman.2023.116821

Ahorsu R, Medina F, Constantí M (2018) Significance and challenges of biomass as a suitable feedstock for bioenergy and biochemical production: a review. Energies 11(12):3366. https://doi.org/10.3390/en11123366

Aliana-Nasharuddin N, Asikin-Mijan N, Abdulkareem-Alsultan G, Saiman M, Alharthi FA, Alghamdi A, Yap YH (2020) Production of green diesel from catalytic deoxygenation of chicken fat oil over a series binary metal oxide-supported MWCNTs. RSC Adv 10:626. https://doi.org/10.1039/C9RA08409F

Alizadeh R, Lund PD, Soltanisehat L (2020) Outlook on biofuels in future studies: a systematic literature review. Renew Sustain Energy Rev 134:110326. https://doi.org/10.1016/j.rser.2020.110326

Al-Saadi A, Mathan B, He Y (2020) Esterification and transesterification over SrO-ZnO/Al_2O_3 as a novel bifunctional catalyst for biodiesel production. Renew Energy 158:388–399. https://doi.org/10.1016/j.renene.2020.05.171

Alsaedi A, Hossain M, Balakrishnan V, Shaah M, Makhtar M, Ismail N, Naushad M, Bathula C (2022) Extraction and separation of lipids from municipal sewage sludge for biodiesel production: kinetics and thermodynamics modeling. Fuel 325:124946. https://doi.org/10.1016/j.fuel.2022.124946

Altalhi AA, Mohamed EA, Morsy SM, Kana NTH, Negm NA (2021) Catalytic manufacture and characteristic valuation of biodiesel-jet achieved from *Jatropa curcas* and waste cooking oils over chemically modified montmorillonite clay. J Mol Liq 340:117175. https://doi.org/10.1016/j.molliq.2021.117175

Ambaye T, Vaccari M, Bonilla-Petriciolet A, Prasad S, van Hullebusch E, Rtimi S (2021) Emerging technologies for biofuel production: a critical review on recent progress, challenges and perspectives. J Environ Manage 290:112627. https://doi.org/10.1016/j.jenvman.2021.112627

Angulo-Mosquera LS, Alvarado-Alvarado AA, Rivas-Arrieta MJ, Cattaneo CR, Rene ER, García-Depraect O (2021) Production of solid biofuels from organic waste in developing countries: a review from sustainability and economic feasibility perspectives. Sci Total Environ 795:148816. https://doi.org/10.1016/j.scitotenv.2021.148816

Anis S, Alhakim R, Wahyudi KAM, Kusumastuti A (2021) Microwave-assisted pyrolysis and distillation of cooking oils for liquid biofuel production. J Anal App Pyrolysis 154:105014. https://doi.org/10.1016/j.jaap.2020.105014

Arazo R, Luna M, Capareda S (2017) Assessing biodiesel production from sewage sludge-derived bio-oil. Biocatal Agric Biotechnol 10:189–196. https://doi.org/10.1016/j.bcab.2017.03.011

Aron NS, Khoo KS, Chew KW, Show PL, Chen WH, Nguyen TH (2020) Sustainability of the four generations of biofuels—a review. Int J Energy Res 44(12):9266–9282. https://doi.org/10.1002/er.5557

Arun J, Gopianath KP, SundarRajan PS, Malola R, Adithya S, Jayaraman RS, Ajay PS (2020) Hydrothermal liquefaction of Scenedesmus obliquus using a novel catalyst derived from clam shells: solid residue as catalyst for hydrogen production. Bioresour Technol 310:123443. https://doi.org/10.1016/j.biortech.2020.123443

Aruwajoye GS, Faloye FD, Kana EG (2020) Process optimization of enzymatic saccharification of soaking assisted and thermal pretreated cassava peels waste for bioethanol production. Waste Biomass Valor 11:2409–2420. https://doi.org/10.1007/s12649-018-00562-0

Ashine F, Kiflie Z, Prabhu SV, Tizazu BZ, Varadharajan V, Rajasimman M, Joo SW, Vasseghian Y, Jayakumar M (2023) Biodiesel production from *Argemone mexicana* oil using chicken eggshell derived CaO catalyst. Fuel 332(2):126166. https://doi.org/10.1016/j.fuel.2022.126166

Asikin-Mijan N, Kareem-Alsultan GA, Mastuli MS, Salmiaton A, Mohamed MA, Lee HV, Taufiq-Yap YH (2022) Single-step catalytic deoxygenation-cracking of tung oil to bio-jet fuel over CoW/silica-alumina catalysts. Fuel 325:124917. https://doi.org/10.1016/j.fuel.2022.124917

Astolfi AL, Rempel A, Cavanhi VA, Alves M, Deamici KM, Colla LM, Costa JA (2020) Simultaneous saccharification and fermentation of *Spirulina* sp. and corn starch for the production of bioethanol and obtaining biopeptides with high antioxidant activity. Bioresour Technol 301:122698. https://doi.org/10.1016/j.biortech.2019.122698

Avinash PI, Rafael RP, Yasmin CSM, Silvio SS (2020) Acid-functionalized magnetic nano catalysts mediated pretreatment of sugarcane straw: an eco-friendly and cost-effective approach. Cellulose 27:7069–7078. https://doi.org/10.1007/s10570-020-03262-y

Ayodeji A, Blessing I, Sunday F (2018) Data on calcium oxide and cow bone catalysts used for soybean biodiesel production. Data Br 18:512–517. https://doi.org/10.1016/j.dib.2018.03.057

Baghani AN, Sadjadi S, Yaghmaeian K, Mahvi AH, Yunesian M, Nabizadeh R (2022) Solid alcohol biofuel based on waste cooking oil: preparation properties, micromorphology, heating value optimization and its application as candle wax. Renew Energy 192:617–630. https://doi.org/10.1016/j.renene.2022.04.100

Bahadorian A, Sadrameli SM, Pahlavanzadeh H, Kashkouli MNI (2023) Optimization study of linseed biodiesel production via in-situ transesterification and slow pyrolysis of obtained linseed residue. Renew Energy 203:10–19. https://doi.org/10.1016/j.renene.2022.12.043

Bai C, Zhu L, Shen F, Qi X (2016) Black liquor-derived carbonaceous solid acid catalyst for the hydrolysis of pretreated rice straw in ionic liquid. Bioresour Technol 220:656–660. https://doi.org/10.1016/j.biortech.2016.08.112

Barbera E, Naurzaliyev R, Asiedu A, Bertucco A, Resurreccion EP, Kumar S (2020) Technoeconomic analysis and life-cycle assessment of jet fuels production from waste cooking oil via in situ catalytic transfer hydrogenation. Renew Energy 160:428–449. https://doi.org/10.1016/j.renene.2020.06.077

Barr MR, Volpe R, Kandiyoti R (2021) Liquid biofuels from food crops in transportation—a balance sheet of outcome. Chem Eng Sci 10:100090. https://doi.org/10.1016/j.cesx.2021.100090

Basir MM, Jamil NAM, Hamdan H (2019) Conversion of jet biofuel range hydrocarbons from palm oil over zeolite hybrid catalyst. Nanomater Nanotechnol 11:1–10. https://doi.org/10.1177/1847980420981536

Bastos RR, Corrêa APL, Luz PT, Filho GNR, Zamian JR, da Conceição LRV (2020) Optimization of biodiesel production using sulfonated carbon-based catalyst from an amazon agro-industrial waste. Energy Convers Manage 205:112457. https://doi.org/10.1016/j.enconman.2019.112457

Batog J, Frankowski J, Wawro A, Łacka A (2020) Bioethanol production from biomass of selected sorghum varieties cultivated as main and second crop. Energies 13:6291. https://doi.org/10.3390/en13236291

Bazargan A, Kostic M, Stamenkovic O, Velkkovic V, McKay G (2015) A calcium oxide-based catalyst derived from palm kernel shell gasification residues for biodiesel production. Fuel 150:519–525. https://doi.org/10.1016/j.fuel.2015.02.046

Bhoi PR, Ouedraogo AS, Soloiu V, Quirino R (2020) Recent advances on catalysts for improving hydrocarbon compounds in bio-oil of biomass catalytic pyrolysis. Renew Sustain Energy Rev 121:109676. https://doi.org/10.1016/j.rser.2019.109676

De Bhowmick G, Sarmah AK, Sen R (2018) Lignocellulosic biorefinery as a model for sustainable development of biofuels and value added products. Bioresour Technol 247:1144–1154. https://doi.org/10.1016/j.biortech.2017.09.163

Biswas B, Kumar A, Kaur R, Krishna BB, Bhaskar T (2021) Catalytic hydrothermal liquefaction of alkali lignin over activated bio-char supported bimetallic catalyst. Bioresour Technol 337:125439. https://doi.org/10.1016/j.biortech.2021.125439

Boey P, Maniam G, Abd Hamid S, Ali D (2011) Utilization of waste cockle shell (*Anadara granosa*) in biodiesel production from palm olein: optimization using response surface methodology. Fuel 90:2353–2358. https://doi.org/10.1016/j.fuel.2011.03.002

Borah AJ, Roy K, Goyal A, Moholkar VS (2019) Mechanistic investigations in biobutanol synthesis via ultrasound-assisted ABE fermentation using mixed feedstock of invasive weeds. Bioresour Technol 272:389–397. https://doi.org/10.1016/j.biortech.2018.10.063

Boro M, Verma AK, Chettri D, Yata VK, Verma AK (2022) Strategies involved in biofuel production from agro-based lignocellulose biomass. Environ Technol Innov 28:102679. https://doi.org/10.1016/j.eti.2022.102679

Bridgwater T (2018) Challenges and opportunities in fast pyrolysis of biomass: part II. Johnson Matthey. Technol Rev 62(2):150–160. https://doi.org/10.1595/205651318X696738

Bu Q, Cao M, Wang M, Vasudevan SV, Mao H (2022) Enhancement of bio-oil quality over self-derived bio-char catalyst via microwave catalytic pyrolysis of peanut shell. J Anal Appl Pyrolysis 164:105534. https://doi.org/10.1016/j.jaap.2022.105534

Buyang Y, Suprapto S, Nugraha RE, Holilah H, Bahruji B, Hantoro R, Jalil A, Oetami TP, Prasetyoko D (2023) Catalytic pyrolysis of *Reutealis trisperma* oil using raw dolomite for bio-oil production. J Anal Appl Pyrolys 169:105852. https://doi.org/10.1016/j.jaap.2022.105852

Capodaglio AG, Callegari A (2018) Feedstock and process influence on biodiesel produced from waste sewage sludge. J Environ Manage 216:176–182. https://doi.org/10.1016/j.jenvman.2017.03.089

Carmona-García E, Marín-Valencia PA, Toro J, Moustakas K, Alzate C (2021) Comparison of acetone-butanol-ethanol fermentation and ethanol catalytic upgrading as pathways for butanol production: a techno-economic and environmental assessment. Biofuel Res J 8(2):1384–1399. https://doi.org/10.18331/BRJ2021.8.2.4

Casabar J, Unpaprom Y, Ramaraj R (2019) Fermentation of pineapple fruit peel wastes for bioethanol production. Biomass Convers Bioref 9:761–765. https://doi.org/10.1007/s13399-019-00436-y

Cheah K, Yusup S, Singh H, Uemura Y, Lam H (2017) Process simulation and techno economic analysis of renewable diesel production via catalytic decarboxylation of rubber seed oil—a case study in Malaysia. J Environ Manage 203(3):950–961. https://doi.org/10.1016/j.jenvman.2017.05.053

Cheah KW, Taylor MJ, Evans G, Samson A, Skoulou V (2022) Overview of biomass conversion to biofuels. In: Yusup S, Rashidi NA (eds) Value-chain of biofuels: fundamentals, technology, and standardization, 1st edn. Elsevier, Chennai, pp 1–48. https://doi.org/10.1016/B978-0-12-824388-6.00007-5

Chen G, Shan R, Shi J, Yan B (2014) Ultrasonic-assisted production of biodiesel from transesterification of palm oil over ostrich eggshell-derived CaO catalysts. Bioresour Technol 171:428–432. https://doi.org/10.1016/j.biortech.2014.08.102

Chen N, Zhang G, Zhang P, Tao X, Wu Y, Wang S, Nabi M (2019) Rice husk-based solid acid for efficient hydrolysis and saccharification of corncob. Bioresour Technol 292:121915. https://doi.org/10.1016/j.biortech.2019.121915

Cherian E, Kalavathy G, Joshi TJ, Phoebe MG, Gurunathan B (2022) Importance of nanocatalyst and its role in biofuel production. In: Gurunathan B, Sahadevan R, Zakaria ZA (eds) Biofuels Bioenergy: Opportunities and Challenges, 1st edn. Elsevier, pp 171–182. https://doi.org/10.1016/B978-0-323-85269-2.00022-8

Chia SR, Nomanbhay S, Ong MY, Shamsuddin AHB, Chew KW, Show PL (2022) Renewable diesel as fossil fuel substitution in Malaysia: a review. Fuel 314:123137. https://doi.org/10.1016/j.fuel.2022.123137

Chingakham C, David A, Sajith V (2019) Fe_3O_4 nanoparticles impregnated eggshell as a novel catalyst for enhanced biodiesel production. Chin J Chem Eng 27:2835–2843. https://doi.org/10.1016/j.cjche.2019.02.022

Chohan NA, Aruwajoye GS, Sewsynker-Sukai Y (2020) Valorisation of potato peel wastes for bioethanol production using simultaneous saccharification and fermentation: Process optimization and kinetic assessment. Renew Energy 146:1031–1040. https://doi.org/10.1016/j.renene.2019.07.042

Choi IH, Hwang KR, Han JS, Lee KH, Yun JS, Lee JS (2015) The direct production of jet-fuel from non-edible oil in a single-step process. Fuel 158:98–104. https://doi.org/10.1016/j.fuel.2015.05.020

Choi YY, Patel AK, Hong ME, Chang WS, Sim SJ (2019) Microalgae bioenergy with carbon capture and storage (BECCS): an emerging sustainable bioprocess for reduced CO_2 emission and biofuel production. Bioresour Technol Rep 7:100270. https://doi.org/10.1016/j.biteb.2019.100270

Chouaibi M, Daoued KB, Riguane K, Rouissi T, Ferrari G (2020) Production of bioethanol from pumpkin peel wastes: comparison between response surface methodology (RSM) and artificial neural networks (ANN). Ind Crops Prod 155:112822. https://doi.org/10.1016/j.indcrop.2020.112822

Chu P, Vanderghem C, MacLean HL, Saville BA (2017) Process modeling of hydrodeoxygenation to produce renewable jet fuel and other hydrocarbon fuels. Fuel 196:298–305. https://doi.org/10.1016/j.fuel.2017.01.097

Cimino S, Lisi L, Romanucci S (2018) Catalysts for conversion of ethanol to butanol: effect of acid-base and redox properties. Catal Today 304:58–63. https://doi.org/10.1016/j.cattod.2017.08.035

European Commission (2019) COM. 640 final—the European green new deal. https://doi.org/10.2307/j.ctvd1c6zh.7

Constantino A, Rodrigues B, Leon R, Barros R, Rposo S (2021) Alternative chemo-enzymatic hydrolysis strategy applied to different microalgae species for bioethanol production. Algal Res 56:102329. https://doi.org/10.1016/j.algal.2021.102329

Crespo I, Hertzog J, Carré V, Aubriet FL, Valle B (2023) Alumina-embedded HZSM-5 with enhanced behavior for the catalytic cracking of biomass pyrolysis bio-oil: Insights into the role of mesoporous matrix in the deactivation by coke. J Anal Appl Pyrolys 172:106009. https://doi.org/10.1016/j.jaap.2023.106009

Dahlke S, Sterling J, Meehan C (2021) Policy and market drivers for advancing clean energy. In: Azad AK (ed) Advances in clean energy technologies, 1st edn. Elsevier, Place, pp 451–548. https://doi.org/10.1016/B978-0-12-821221-9.00012-8

Dahmen N, Lewandowski I, Zibek S, Weidtmann A (2019) Integrated lignocellulosic value chains in a growing bioeconomy: Status quo and perspectives. Glob Change Biol Bioenergy 11(1):107–117. https://doi.org/10.1111/gcbb.12586

Dai L, Zeng Z, Tian X, Jiang L, Yu Z, Wu Q, Wang Y, Liu Y, Ruan R (2019) Microwave-assisted catalytic pyrolysis of torrefied corn cob for phenol-rich bio-oil production over Fe modified bio-char catalyst. J Anal Appl Pyrolys 143:104691. https://doi.org/10.1016/j.jaap.2019.104691

Daimary N, Eldiehy KSH, Bora N, Boruah P, Rather MA, Mandal M, Bora U, Deka D (2023) Towards integrated sustainable biofuel and chemical production: an application of banana pseudostem ash in the production of biodiesel and recovery of lignin from bamboo leaves. Chemosphere 314:137625. https://doi.org/10.1016/j.chemosphere.2022.137625

Davidson DJ (2019) Exnovating for a renewable energy transition. Nat Energy 4:254–256. https://doi.org/10.1038/s41560-019-0369-3

Del Amo-Mateos E, López-Linares JC, García-Cubero MT, Lucas S, Coca M (2022) Green biorefinery for sugar beet pulp valorisation: microwave hydrothermal processing for pectooligosaccharides recovery and biobutanol production. Ind Crops Products 184:115060. https://doi.org/10.1016/j.indcrop.2022.115060

Demiray E, Karatay S, Dönmez G (2020) Efficient bioetanol production from pomegranate peels by newly isolated *Kluyveromyces marxianus*. Energy Sour 42:709–718. https://doi.org/10.1080/15567036.2019.1600621

Devarajan Y, Munuswamy DB, Subbiah G, Vellaiyan S, Nagappan B, Varuvel EG, Thangaraja J (2022) Inedible oil feedstocks for biodiesel production: a review of production technologies and physicochemical properties. Sustain Chem Pharma 30:100840. https://doi.org/10.1016/j.scp.2022.100840

Dhiman S, Mukherjee G (2023) Utilization of wood waste for biofuel production: a biorefining perspective. Mater Today: Proc (in Press). https://doi.org/10.1016/j.matpr.2022.12.009

Dong T, Teymouri A, Adams KJ, Kumar S (2018) Evaluation of lipid extractability after flash hydrolysis of algae. Fuel. https://doi.org/10.1016/j.fuel.2018.03.044

Donoso D, Bolonio D, Ballesteros R, Lapuerta M, Canoira L (2022) Hydrogenated orange oil: a waste derived drop-in biojet fuel. Renew Energy 188:1049–1058. https://doi.org/10.1016/j.renene.2022.02.078

Douvartzides SL, Charisiou ND, Papageridis KN, Goula MA (2019) Green diesel: Biomass feedstocks, production technologies, catalytic research, fuel properties and performance in compression ignition internal combustion engines. Energies 12(5):809. https://doi.org/10.3390/en12050809

Du H, Yu Q, Liu G, Li J, Zhang J, Wang W, Duan G, Meng Y, Xie H (2022) Catalytic deoxygenation of carboxyl compounds in the hydrothermal liquefaction crude bio-oil via in-situ hydrogen supply by CuO–CeO2/γ-Al_2O_3 catalyst. Fuel 317:123367. https://doi.org/10.1016/j.fuel.2022.123367

Duan D, Feng Z, Zhang Y, Zhou T, Xu Z, Wang Q, Zhao Y, Wang C, Ruan R (2022) Corncob pyrolysis: improvement in hydrocarbon group types distribution of bio oil from co-catalysis over HZSM-5 and activated carbon. Waste Manage 141:8–15. https://doi.org/10.1016/j.wasman.2022.01.028

El-Araby R, Abdelkader E, Diwani GE, Hawash SI (2020) Bio-aviation fuel via catalytic hydrocracking of waste cooking oils. Bull Natl Res Cent 44:177–184. https://doi.org/10.1186/s42269-020-00425-6

Energy Statistics Pocketbook (2021) United Nation. https://unstats.un.org/unsd/energystats/pubs/documents/2021pb-web.pdf. Accessed 8 Jun 2023

Erukainure OL, Ebuehi OAT, Chaudhary M, Mesaik MA, Shukralla A, Muhammad A, Mesaik A, Shukralla A, Muhammad A (2016) Orange peel extracts: chemical characterization, antioxidant, antioxidative burst, and phytotoxic activities. J Diet Suppl 13:585–594. https://doi.org/10.3109/19390211.2016.1150932

Fadhilah NA, Islam MN, Rosli R (2023) Techno-economic analysis of sawdust and rice husk co-pyrolysis for bio-oil production. Bioresour Technol Rep 21:101233. https://doi.org/10.1016/j.biteb.2022.101233

Fakayode O, Akpabli-Tsigbe ND, Wahia H, Tu S, Ren M, Zhou C, Ma H (2021) Integrated bioprocess for bio-ethanol production from watermelon rind biomass: ultrasound-assisted deep eutectic solvent pretreatment, enzymatic hydrolysis and fermentation. Renew Energy 180:258–270. https://doi.org/10.1016/j.renene.2021.08.057

Farissi HE, Talhaoui A, Bachiri AE (2022) Influence of pyrolysis process on the production of bio-oil used as alternative green energy from *Pistacia lentiscus* Lalances: overview, IEA world energy statistics and bala. J Anal Appl Pyrolysis 168:105781. https://doi.org/10.1016/j.jaap.2022.105781

Farmanbordar S, Amiri H, Karimi K (2018) Simultaneous organosolv pretreatment and detoxification of municipal solid waste for efficient biobutanol production. Bioresour Technol 270:236–244. https://doi.org/10.1016/j.biortech.2018.09.017

Foroutan R, Mohammadi R, Razeghi J, Ramavandi B (2021) Biodiesel production from edible oils using algal biochar/CaO/K_2CO_3 as a heterogeneous and recyclable catalyst. Renew Energy 168:1207–1216. https://doi.org/10.1016/j.renene.2020.12.094

Gao J, Zeng J, Zhu S, Ma H, Yao R, Zhao Y, He Z (2023) In-situ catalytic bio-oil production from hydrothermal liquefaction of Cu-impregnated water hyacinth: screening of reaction parameters. J Energy Inst 109:101308. https://doi.org/10.1016/j.joei.2023.101308

Ghorbannezhad P, Soleymani N, Abbasi M (2023) Co-pyrolysis of municipal and horticultural wastes for enhanced biochar and bio-oil production: a response surface methodology approach. Fuel 350:128795. https://doi.org/10.1016/j.fuel.2023.128795

Gil A (2022) Challenges on waste-to-energy for the valorization of industrial wastes: electricity, heat and cold, bioliquids and biofuels. Environ Nanotechnol Monit Manag 17:100615. https://doi.org/10.1016/j.enmm.2021.100615

Global Bioenergy Statistics (2020) World bioenergy association. http://www.worldbioenergy.org/uploads/201210%20WBA%20GBS%202020.pdf. Accessed 8 Mar 2023

Gohain M, Laskar K, Paul AK, Daimary N, Maharana M, Goswami IK, Hazarika A, Bora U, Deka D (2020) Carica papaya stem: a source of versatile heterogeneous catalyst for biodiesel production and C–C bond formation. Renew Energy 147:541–555. https://doi.org/10.1016/j.renene.2019.09.016

Gohain M, Hasin M, Eldiehy KS, Bardhan P, Laskar K, Phukon H, Mandal M, Kalita D, Deka D (2021) Bio-ethanol production: a route to sustainability of fuels using bio-based heterogeneous catalyst derived from waste. Process Saf Environ Prot 146:190–200. https://doi.org/10.1016/j.psep.2020.08.046

Gomes AD, Rodrigues MI, Passos DD, Castro AM, Anna LM Jr, NP (2019) Acetone-butanol-ethanol fermentation from sugarcane bagasse hydrolysates: utilization of C5 and C6 sugars. Electron J Biotechnol 42:16–22. https://doi.org/10.1016/j.ejbt.2019.10.004

Goswami L, Kayalvizhi R, Dikshit PK, Sherpa KC, Roy S, Kushwaha A, Kim BS, Banerjee R, Jacob S, Rajak RC (2022) A critical review on prospects of bio-refinery products from second and third generation biomasses. Chem Eng J 448:137677. https://doi.org/10.1016/j.cej.2022.137677

Gouran A, Aghel B, Nasirmanesh F (2021) Biodiesel production from waste cooking oil using wheat bran ash as a sustainable biomass. Fuel 295:12054. https://doi.org/10.1016/j.fuel.2021.120542

Gousi M, Andriopoulou C, Bourikas K, Ladas S, Sotiriou M, Kordulis C, Lycourghioti A (2017) Green diesel production over nickel-alumina co-precipitated catalysts. Appl Catal 536:45–56. https://doi.org/10.1016/j.apcata.2017.02.010

Gousi M, Kordouli E, Bourikas K, Symianakis E, Ladas S, Kordulis C, Lycourghiotis A (2020) Green diesel production over nickel-alumina nanostructured catalysts promoted by copper. Energies 13(14):3707. https://doi.org/10.3390/en1314707

Gu Y, Han C, Huang J, Vinokurov VA, Huan W (2022) CZnAlOOH catalysts with Cu^0/Cu^+ constructed by two-step hydrolysis for ethanol production from syngas. Fuel 322:124111. https://doi.org/10.1016/j.fuel.2022.124111

Günay ME, Türker L, Tapan NA (2019) Significant parameters and technological advancements in biodiesel production systems. Fuel 250:27–41. https://doi.org/10.1016/j.fuel.2019.03.147

Hafeez S, Al-Salem S, Papageridis K, Charisiou N, Goula M, Manos G, Constantinou A (2021) Theoretical investigation of the deactivation of Ni supported catalysts for the catalytic deoxygenation of palm oil for green diesel production. Catal 11(6):747. https://doi.org/10.3390/catal11060747

Hajilary N, Shirazian S, Rezakazemi M (2019) Biofuel types and membrane separation. Environ Chem Lett 17:1–18. https://doi.org/10.1007/s10311-018-0777-9

Haldar D, Purkait MK (2021) A review on the environment-friendly emerging techniques for pretreatment of lignocellulosic biomass: mechanistic insight and advancements. Chemosphere 264:128523. https://doi.org/10.1016/j.chemosphere.2020.128523

Hanafi SA, Elmelawy MS, Shalaby NH, El-Syed HA, Eshaq G, Mostafa MS (2016) Hydrocracking of waste chicken fat as a cost effective feedstock for renewable fuel production: a kinetic study. Egypt J Pet 25(4):531–537. https://doi.org/10.1016/j.ejpe.2015.11.006

Hapsari MT, Trisunaryanti W, Falah II, Permata ML (2020) Coating of Pd and Co on mordenite for a catalyst of hydrotreating of cashew nut shell liquid into biofuel. Indone J Chem 20(5):1092–1100. https://doi.org/10.22146/ijc.48633

Hazrat MA, Rasul MG, Khan MM, Ashwath N, Rufford TE (2019) Emission characteristics of waste tallow and waste cooking oil based ternary biodiesel fuels. Energy Proc 160:842–847. https://doi.org/10.1016/j.egypro.2019.02.149

Higai D, Lee C, Lang J, Qian EW (2021) Saccharification of cellulose using biomass-derived activated carbon-based solid acid catalysts. Fuel Process Technol 215:106738. https://doi.org/10.1016/j.fuproc.2021.106738

Hijosa-Valsero M, Paniagua-García AI, Díez-Antolínez R (2017) Biobutanol production from apple pomace: the importance of pretreatment methods on the fermentability of lignocellulosic agro-food wastes. Appl Microbiol Biotechnol 101:8041–8052. https://doi.org/10.1007/s00253-017-8522-z

Hijosa-Valsero M, Paniagua-García AI, Díez-Antolínez R (2018) Industrial potato peel as a feedstock for biobutanol production. New Biotechnol 46:54–60. https://doi.org/10.1016/j.nbt.2018.07.002

Hongloi N, Prapainainar P, Prapainainar C (2022) Review of green diesel production from fatty acid deoxygenation over Ni-based catalysts. Mol Catal 523:111696. https://doi.org/10.1016/j.mcat.2021.111696

Hsu HW, Chang YS, Wang WC (2021) Techno-economic analysis of used cooking oil to jet fuel production under uncertainty through three-, two-, and one-step conversion processes. J Clean Prod 289:125778. https://doi.org/10.1016/j.clepro.2020.125778

Husin H, Riza M, Faisal M (2023) Biodiesel production using waste banana peel as renewable base catalyst. Mater Today. https://doi.org/10.1016/j.matpr.2023.02.400

Hussain M, Biradar C (2023) Production of hydroprocessed renewable diesel from Jatropha oil and evaluation of its properties. Mater Today 72:1420–1425. https://doi.org/10.1016/j.matpr.2022.09.341

Hussain I, Ganiyu SA, Alasiri H, Alhooshani K (2022) A state-of-the-art review on waste plastics-derived aviation fuel: unveiling the heterogeneous catalytic systems and techno-economy feasibility of catalytic pyrolysis. Energy Convers Manage 274:116463. https://doi.org/10.1016/j.enconman.2022.116433

Huzir N, Aziz M, Ismail SB, Abdullah B, Mahmood N, Umor NA, Muhammad SA (2018) Agro-industrial waste to biobutanol production: eco-friendly biofuels for next generation. Renew Sustain Energy Rev 94:476–485. https://doi.org/10.1016/j.rser.2018.06.036

IBÁ (2019) Report 2019 Brazilian Tree Industry [WWW Document]. https://iba.org/datafiles/publicacoes/relatorios/iba-relatorioanual2019.pdf. Accessed 22 Nov 2020

Iglesias SP, Miyazaki MR, Mariano AP, Franco TT (2021) Techno-economic assessment of bio-oil produced from Eucalyptus forestry residues. Ind Crops Prod 171:113936. https://doi.org/10.1016/j.indcrop.2021.113936

Iha OK, Martins GB, Ehlert E, Montenegro MA, Sucupira RR, Suarez PA (2018) Extraction and characterization of passion fruit and guava oils from industrial residual seeds and their application as biofuels. J Braz Chem Soc 29:2089–2095. https://doi.org/10.21577/0103-5053.20180083

Inayat A, Rocha-Meneses L, Ghenai C, Abdallah M, Shanableh A, Al-Ali K, Alghfeli A, Alsuwaidi R (2022) Co-pyrolysis for bio-oil production via fixed-bed reactor using date seeds and plastic waste as biomass. Case Studi Therm Eng 31:101841. https://doi.org/10.1016/j.csite.2022.101841

International Energy Agency (2021) Word energy balances: overview, IEA world energy statistics and balances (database). https://doi.org/10.1787/45be1845-en

Jamil F, Al-Mutahseb A, Al-Haj L, Al-Hinai M, Baawain, (2017) Phoenix dactylifera kernel oil used as potential source for synthesizing jet fuel and green diesel. Energy Proc 118:35–39. https://doi.org/10.1016/j.egypro.2017.07.006

Jin Q, Qureshi N, Wang H, Huang H (2019) Acetone-butanol-ethanol (ABE) fermentation of soluble and hydrolyzed sugars in apple pomace by *Clostridium beijerinckii* P260. Fuel 244:536–544. https://doi.org/10.1016/j.fuel.2019.01.177

Jin Y, Zhang L, Yi Z, Fang Y, Zhao H (2022) Waste-to-energy: biobutanol production from cellulosic residue of sweet potato by *Clostridia acetobutylicum*. Environ Eng Res 27:210372. https://doi.org/10.4491/eer.2021.372

Johansson A, Molinder R, Vikstrom T, Wiinikka H (2021) Particle formation during suspension combustion of different biomass powders and their fast pyrolysis bio-oils and biochars. Fuel Process Technol 218:106868. https://doi.org/10.1016/j.fuproc.2021.106868

Julio AA, Milessi TS, Ocampo E, Silva E, Yepes D, Escobar JC (2022) Techno-economic and environmental potential of Renewable Diesel as complementation for diesel and biodiesel in Brazil: a comprehensive review and perspectives. J Clean Prod 371:133431. https://doi.org/10.1016/j.jclepro.2022.133431

Kaewtrakulchai N, Kaewmeesri R, Itthibenchapong V, Eiad-Ua A, Faungnawakij K (2020) Palm oil conversion to bio-jet and green diesel fuels over cobalt phosphide on porous carbons derived from palm male flowers. Catalysts 10:694. https://doi.org/10.3390/catal10060694

Kamaruzaman M, Taufiq-Yap YH, Derawi D (2020) Green diesel production from palm fatty acid distillate over SBA-15-supported nickel, cobalt, and nickel/cobalt catalysts. Biomass Bioenergy 134:105476. https://doi.org/10.1016/j.biombioe.2020.105476

Kang KE, Jeong JS, Kim Y, Min J, Moon SK (2019) Development and economic analysis of bioethanol production facilities using lignocellulosic biomass. J Biosci Bioeng 128(4):475–479. https://doi.org/10.1016/j.jbiosc.2019.04.004

Kannapu HP, Pyo S, Lam SS, Jae J, Rhee GH, Khan MA, Jeon BH, Park YK (2022) Bioresour Technol 359:127500. https://doi.org/10.1016/j.biortech.2022.127500

Kawashima A, Matsubara K, Honda K (2008) Development of heterogeneous base catalysts for biodiesel production. Bioresour Technol 99:3439–3443. https://doi.org/10.1016/j.biortech.2007.08.009

Keera ST, Sabagh SM, Taman AR (2018) Castor oil biodiesel production and optimization. Egypt J Pet 27:979–984. https://doi.org/10.1016/j.ejpe.2018.02.007

Kelly S (2021) U.S. renewable fuels market could face feedstock deficit. Reuters: Energy

Khan H, Iqbal T, Ali C, Javaid A, Cheema I (2020) Sustainable biodiesel production from waste cooking oil utilizing waste ostrich (*Struthio camelus*) bones derived heterogeneous catalyst. Fuel 277:1–10. https://doi.org/10.1016/j.fuel.2020.118091

Khan MSA, Grioui N, Halouani K, Benelmir R (2022) Techno-economic analysis of production of bio-oil from catalytic pyrolysis of olive mill wastewater sludge with two different cooling mechanisms. Energy Convers Manag X 13:100170. https://doi.org/10.1016/j.ecmx.2021.100170

Khedkar MA, Nimbalkar PR, Chavan PV, Chendake YJ, Bankar SB (2017) Cauliflower waste utilization for sustainable biobutanol production: revelation of drying kinetics and bioprocess development. Bioproc Biosyst Eng 40:1493–1506. https://doi.org/10.1007/s00449-017-1806-y

Knothe G (2010) Biodiesel and renewable diesel: a comparison. Prog Energy Combust Sci 36(3):364–373. https://doi.org/10.1016/j.pecs.2009.11.004

Kopperi H, Mohan SV (2023) Catalytic hydrothermal deoxygenation of sugarcane bagasse for energy dense bio-oil and aqueous fraction acidogenesis for biohydrogen production. Bioresour Technol 379:128954. https://doi.org/10.1016/j.biortech.2023.128954

Kordouli E, Pawelec B, Bourikas K, Kordulis C, Fierro J, Lycourghiotis A (2018) Mo promoted Ni–Al_2O_3 co-precipitated catalysts for green diesel production. Appl Catal: Environ 229:139–154. https://doi.org/10.1016/j.apcatb.2018.02.015

Kothari R, Vashishtha A, Singh H, Pathak V, Tyagi V, Yadav BC, Ashokkumar V, Singh DP (2020) Assessment of Indian bioenergy policy for sustainable environment and its impact for rural India: strategic implementation and challenges. Environ Technol Innov 20:101078. https://doi.org/10.1016/j.eti.2020.101078

Koul B, Yakoob M, Shah MP (2022) Agricultural waste management strategies for environmental sustainability. Environ Res 206:112285. https://doi.org/10.1016/j.envres.2021.112285

Kruasuwan W, Puseenam A, Am-in S, Trakarnpaiboon S, Sornlek W, Kocharin K, Jindamorakot S, Tanapongpipat S, Bai FY, Roongsawang N (2022) Evaluation of thermotolerant and ethanol-tolerant *Saccharomyces cerevisiae* as an alternative strain for bioethanol production from industrial feedstocks. Biotech 13:1–11. https://doi.org/10.1007/s13205-022-03436-4

Kumar R, Strezov V, Lovell E, Kan T, Weldekidan H, He J, Jahan S, Dastjerdi B, Scott J (2019) Enhanced bio-oil deoxygenation activity by Cu/zeolite and Ni/zeolite catalysts in combined in-situ and ex-situ biomass pyrolysis. J Anal Appl Pyrolysis 140:148–160. https://doi.org/10.1016/j.jaap.2019.03.008

Kumar B, Bhardwaj N, Agrawal K, Chaturvedi V, Verma P (2020) Current perspective on pretreatment technologies using lignocellulosic biomass: an emerging biorefinery concept. Fuel Process Technol 199:106244. https://doi.org/10.1016/j.fuproc.2019.106244

Kumar N, Koul R, Singh RC (2022) Comparative analysis of ternary blends of renewable diesel, diesel and ethanol with diesel. Sustain Energy Technol Assess 50:101828. https://doi.org/10.1016/j.seta.2021.101828

Lahiri A, Daniel S, Kanthapazham R, Vanaraj R, Thambidurai A, Peter LS (2023) A critical review on food waste management for the production of materials and biofuel. J Hazard Mater Adv 10:100266. https://doi.org/10.1016/j.hazadv.2023.100266

Lamba N, Gupta K, Modak J, Madras G (2017) Biodiesel synthesis from *Calophyllum inophyllum* oil with different supercritical fluids. Bioresour Technol 241:767–774. https://doi.org/10.1016/j.biortech.2017.06.027

Lane J (2019) Biofuels Mandates around the World. Biofuels Digest. https://www.biofuelsdigest.com/bdigest/2019/12/31/the-digests-biofuels-mandates-around-the-world-2020/

Laskar L, Rajkumari K, Gupta R, Chatterjee S, Paul B, Rokhum L (2018) Waste snail shell derived heterogeneous catalyst for biodiesel production by the transesterification of soybean oil. RSC Adv 8:20131–20142. https://doi.org/10.1039/C8RA02397B

Lee S, Sankaran R, Chew K, Tan C, Krishnamoorthy R, Chu D, Show P (2019) Waste to bioenergy: a review on the recent conversion technologies. BMC Energy 1(4):1–22. https://doi.org/10.1186/s42500-019-0004-7

Lee D, Choi J, Lee YW, Lee JM (2021) Design and economic analysis of biodiesel production process of simultaneous supercritical transesterification and partial hydrogenation using soybean oil with Pd/Al_2O_3 catalyst. Chem Eng Res Des 172:264–279. https://doi.org/10.1016/j.cherd.2021.06.010

Leong WH, Zaine SN, Ho YC, Uemura Y, Lam MK, Khoo KS, Kiatkittipong W, Cheng CK, Show PL, Lim JW (2019) Impact of various microalgal-bacterial populations on municipal wastewater bioremediation and its energy feasibility for lipid-based biofuel production. J Environ Manage 249:109384. https://doi.org/10.1016/j.jenvman.2019.109384

Li X, Mupondwa E, Tabil L (2018a) Technoeconomic analysis of biojet fuel production from camelina at commercial scale: Case of Canadian Prairies. Bioresour Technol 249:196–205. https://doi.org/10.1016/j.biortech.2017.09.183

Li Z, Huang Z, Ding S, Li F, Wang Z, Lin H, Chen C (2018b) Catalytic conversion of waste cooking oil to fuel oil: catalyst design and effect of solvent. Energy 157:270–277. https://doi.org/10.1016/j.energy.2018.05.156

Li Y, Shaheen SM, Rinklebe J, Ma N, Yang Y, Ashraf MA, Chen X, Peng WX (2021) Pyrolysis of *Aesculus chinensis* bunge seed with Fe_2O_3/NiO as nanocatalysts for the production of bio-oil material. J Hazard Mater 416:126012. https://doi.org/10.1016/j.jhazmat.2021.126012

Li Q, Yuan X, Hu X, Meers E, Ong HC, Chen WH, Duan P, Zhang S, Lee KB, Ok YS (2022a) Co-liquefaction of mixed biomass feedstocks for bio-oil production: a critical review. Renew Sustain Energy Rev 154:111814. https://doi.org/10.1016/j.rser.2021.111814

Li Z, Liang Y, Ni W, Liao Q, Xu N, Li L, Zheng J, Zhang H (2022b) Pipesharing: economic-environmental benefits from transporting biofuels through multiproduct pipelines. Appl Energy 311:118684. https://doi.org/10.1016/j.apenergy.2022.118684

Li P, Niu B, Pan H, Zhang Y, Long D (2023) Production of hydrocarbon-rich bio-oil from catalytic pyrolysis of waste cooking oil over nickel monoxide loaded corn cob-derived activated carbon. J Clean Prod 384:135653. https://doi.org/10.1016/j.jclepro.2022.135653

Lim HY, Tang SH, Chai YH, Yusup S, Lim MT (2022) Co-pyrolysis of plastics and food waste mixture under flue gas condition for bio-oil production. Sustain Energy Technol Assess 54:102826. https://doi.org/10.1016/j.seta.2022.102826

Lin CY, Lu C (2021) Development perspectives of promising lignocellulose feedstocks for production of advanced generation biofuels: a review. Renew Sustain Energy Rev 136:110445. https://doi.org/10.1016/j.rser.2020.110445

Lin X, Lei H, Huo E, Qian M, Mateo W, Zhang Q, Zhao Y, Wang C, Villota E (2020) Enhancing jet fuel range hydrocarbons production from catalytic co-pyrolysis of Douglas fir and low-density polyethylene over bifunctional activated carbon catalysts. Energy Convers Manage 211:112757. https://doi.org/10.1016/j.enconman.2020.112757

Lin YC, Shangdiar S, Chen SC, Cho CA, Datov A (2021) A study on different parameters affecting the saccharification rate of *Typha orientalis* pretreated with Ionic Liquids (ILs) and microwave irradiation for bioethanol production by using response surface methodology. Catal Comm 150:106265. https://doi.org/10.1016/j.catcom.2020.106265

Liu G, Yan B, Chen G (2013) Technical review on jet fuel production. Renew Sustain Energy Rev 23:59–70. https://doi.org/10.1016/j.rser.2013.03.025

Liu J, Lei J, He J, Deng L, Wang L, Fan K, Rong L (2015) Hydroprocessing of jatropha oil for production of green diesel over non-sulfided Ni-PTA/Al_2O_3 catalyst. Sci Reports 5(1):11327. https://doi.org/10.1038/srep11327

Liu S, Wu G, Syed-Hassan SS, Li B, Hu X, Zhou J, Huang Y, Zhang S, Zhang H (2022) Catalytic pyrolysis of pine wood over char-supported Fe: bio-oil upgrading and catalyst regeneration by CO_2/H_2O. Fuel 307:121778. https://doi.org/10.1016/j.fuel.2021.121778

Liu Y, Cruz-Morales P, Zangar A, Belcher MS, Pang B, Englund E, Dan Q, Yin K, Keasling JD (2021) Biofuels for a sustainable future. Cell 184:1636–1647. https://doi.org/10.1016/j.cell.2021.01.052

López-Linares JC, García-Cubero MT, Coca M, Lucas S (2021) Efficient biobutanol production by acetone-butanol-ethanol fermentation from spent coffee grounds with microwave assisted dilute sulfuric acid pretreatment. Bioresour Technol 320:124348. https://doi.org/10.1016/j.biortech.2020.124348

López-Linares JC, Coca M, Plaza PE, Lucas S, García-Cubero MT (2023) Waste-to-fuel technologies for the bioconversion of carrot discards in to biobutanol. Renew Energy 202:362–369. https://doi.org/10.1016/j.renene.2022.11.093

Lu S, Wang Q, Liang Z, Wang W, Liang C, Wang Z, Yuan Z, Lan P, Qi W (2021) Saccharification of sugarcane bagasse by magnetic carbon-based solid acid pretreatment and enzymatic hydrolysis. Ind Crops Prod 160:113159. https://doi.org/10.1016/j.indcrop.2020.113159

Lu H, Yadav V, Zhong M, Bilal M, Taherzadeh MJ, Iqbal HM (2022) Bioengineered microbial platforms for biomass-derived biofuel production—a review. Chemosphere 288:132528. https://doi.org/10.1016/j.chemosphere.2021.132528

Luo H, Zheng P, Bilal M, Xie F, Zeng Q, Zhu C, Yang R, Wang Z (2020) Efficient bio-butanol production from lignocellulosic waste by elucidating the mechanisms of *Clostridium acetobutylicum* response to phenolic inhibitors. Sci Total Environ 710:136399. https://doi.org/10.1016/j.scitotenv.2019.136399

Lycourghiotis S, Kordouli E, Sygellou L, Bourikas K, Kordulis C (2019) Nickel catalysts supported on palygorskite for transformation of waste cooking oils into green diesel. Appl Catal 259:118059. https://doi.org/10.1016/j.apcatb.2019.118059

Mahapatra S, Kumar D, Singh B, Sachan PK (2021) Biofuels and their sources of production: a review on cleaner sustainable alternative against conventional fuel, in the framework of the food and energy nexus. Energy Nexus 4:100036. https://doi.org/10.1016/j.nexus.2021.100036

Makcharoen M, Kaewchada A, Akkarawatkhoosith N, Jaree A (2021) Biojet fuel production via deoxygenation of crude palm kernel oil using Pt/C as catalyst in a continuous fixed bed reactor. Energy Convers Manag 12:100125. https://doi.org/10.1016/j.ecmx.2021.100125

Malode SJ, Gaddi SA, Kamble PJ, Nalwad AA, Muddapur UM, Shetti NP (2022) Recent evolutionary trends in the production of biofuels. Mater Scie Energy Technol 5:262–277. https://doi.org/10.1016/j.mset.2022.04.001

Mamo TT, Mekonnen Y (2019) Microwave-assisted biodiesel production from microalgae, *Scenedesmus* Species, using goat bone-made nano-catalyst. Appl Biochem Biotechnol 190:1147–1162. https://doi.org/10.1007/s12010-019-03149-0

Mardiana S, Azhari N, Ilmi T, Kadja G (2022) Hierarchical zeolite for biomass conversion to biofuel: a review. Fuel 309:122119. https://doi.org/10.1016/j.fuel.2021.122119

Mares EKL, Gonçalves M, Arrais LPTS, Filho GND, Zamian JR, Conceição LRV (2021) Acai seed ash as a novel basic heterogeneous catalyst for biodiesel synthesis: optimization of the biodiesel production process. Fuel 299:120887. https://doi.org/10.1016/j.fuel.2021.120887

Martinez-Hernandez E, Ramírez-Verduzco LF, Amezcua-Allieri MA, Aburto J (2019) Process simulation and techno-economic analysis of bio-jet fuel and green diesel production—minimum selling prices. Chem Eng Res Des 146:60–70. https://doi.org/10.1016/j.cherd.2019.03.042

Martins-Vieira JC, Lachos-Perez D, Draszewski CP, Celante D, Castilhos F (2023) Sugar, hydrochar and bio-oil production by sequential hydrothermal processing of corn cob. J Supercrit Fluids 194:105838. https://doi.org/10.1016/j.supflu.2023.105838

Mateo W, Lei H, Villota E, Qian M, Zhao Y, Huo E, Zhang Q, Lin X, Wang C, Huang Z (2020) Synthesis and characterization of sulfonated activated carbon as a catalyst for bio-jet fuel production from biomass and waste plastics. Bioresour Technol 297:122411. https://doi.org/10.1016/j.biortech.2019.122411

Meng J, Park J, Tilotta D, Park S (2012) The effect of torrefaction on the chemistry of fast-pyrolysis bio-oil. Bioresour Technol 111:439–446. https://doi.org/10.1016/j.biortech.2012.01.159

Mohammed ST, Hamad KI, Gheni SA, Aqar DY, Ahmed SMR, Mahmood MA, Ceylan S, Abdullah H (2022) Enhancement of stability of Pd/AC deoxygenation catalyst for hydrothermal production of green diesel from waste cooking oil. Chem Eng Sci 251:117489. https://doi.org/10.1016/j.ces.2022.117489

Moreira J, De Rezende D, Pasa V (2020) Deoxygenation of Macauba acid oil over Co-based catalyst supported on activated biochar from Macauba endocarp: a potential and sustainable route for green diesel and biokerosene production. Fuel 269:117253. https://doi.org/10.1016/j.fuel.2020.117253

Muharja M, Darmayanti RF, Fachri BA, Palupi B, Rahmawati I, Rizkiana MF, Amini HW, Putri D, Setiawan F, Asrofi M, Widjaja A, Halim A (2023) Biobutanol production from cocoa pod husk through a sequential green method: depectination, delignification, enzymatic hydrolysis, and extractive fermentation. Bioresour Technol Rep 21:101298. https://doi.org/10.1016/j.biteb.2022.101298

Mullen CA, Boateng AA (2019) Mild hydrotreating of bio-oils with varying oxygen content produced via catalytic fast pyrolysis. Fuel 245:360–367. https://doi.org/10.1016/j.fuel.2019.02.027

Muniyappan D, Junior A, Vinayakaselvi A, Ramanathan A (2023) Synergistic recovery of renewable hydrocarbon resources via microwave co-pyrolysis of biomass residue and plastic waste over spent toner catalyst towards sustainable solid waste management. Energy 278:127652. https://doi.org/10.1016/j.energy.2023.127652

Nabi MN, Hussam WK, Rashid AB, Islam J, Islam S, Afroz H (2022) Notable improvement of fuel properties of waste tire pyrolysis oil by blending a novel pumpkin seed oil-biodiesel. Energy Rep 8:112–119. https://doi.org/10.1016/j.egyr.2022.10.246

Nanda S, Berruti F (2021) Municipal solid waste management and landfilling technologies: a review. Environ Chem Lett 19:1433–1456. https://doi.org/10.1007/s10311-020-01100-y

Nata IF, Irawan C, Mardina P, Lee CK (2015) Carbon-based strong solid acid for cornstarch hydrolysis. J Solid State Chem 230:163–168. https://doi.org/10.1016/j.jssc.2015.07.005

Nayab R, Imran M, Ramzan M, Muhammad M, Taj MB, Akhtar MN, Iqbal HM (2022) Sustainable biodiesel production via catalytic and non-catalytic transesterification of feedstock materials—a review. Fuel 328:125254. https://doi.org/10.1016/j.fuel.2022.125254

Nazir MH, Ayoub M, Zahid I, Shamsuddin RB, Yusup S, Ameen M, Qadeer UM (2021) Development of lignin based heterogeneous solid acid catalyst derived from sugarcane bagasse for microwave assisted-transesterification of waste cooking oil. Biomass Bioenergy 146:105978. https://doi.org/10.1016/j.biombioe.2021.105978

Nimbalkar PR, Khedkar MA, Chavan PV, Bankar SB (2018) Biobutanol production using pea pod waste as substrate: Impact of drying on saccharification and fermentation. Renew Energy 117:520–529. https://doi.org/10.1016/j.renene.2017.10.079

Niyas MM, Shaija A (2023) Biodiesel production from coconut waste cooking oil using novel solar powered rotating flask oscillatory flow reactor and its utilization in diesel engine. Thermal Sci Eng Prog 40:101794. https://doi.org/10.1016/j.tsep.2023.101794

Nogales-Delgado S, Sánchez N, Encinar JM (2020) Valorization of *Cynara cardunculus* L. oil as the basis of a biorefinery for biodiesel and biolubricant production. Energies 13(19):5085. https://doi.org/10.3390/en13195085

Olkiewicz M, Plechkova N, Earle M, Fabregat A, Stüber F, Foruny A, Font J, Bengoa C (2016) Biodiesel production from sewage sludge lipids catalysed by Brønsted acidic ionic liquids. Appl Catal 181:738–746. https://doi.org/10.1016/j.apcatb.2015.08.039

Omidkar A, Xu H, Li Z, Haddadian K, Song H (2023) Techno-economic and life cycle assessment of renewable diesel production via methane-assisted catalytic waste cooking oil upgrading. J Clean Prod 414:137512. https://doi.org/10.1016/j.jclepro.2023.137512

Ong HC, Chen WH, Farooq A, Gan YY, Lee KT, Ashokkumar V (2019) Catalytic thermochemical conversion of biomass for biofuel production: a comprehensive review. Renew Sust Energ Rev 113:109266. https://doi.org/10.1016/j.rser.2019.109266

Organization of the Petroleum Exporting Countries (2023) OPEC monthly oil market report. https://momr.opec.org/pdf-download/. Accessed 8 Sept 2023

Palmisano G, Jitan SA, Garlisi C (2022) Green heterogeneous catalysis. In: Palmisano G, Jitan SA, Garlisi C (eds) Heterogeneous catalysis: fundamentals, engineering and characterizations, 1st edn. Elsevier, Chennai, pp 193–242. https://doi.org/10.1016/B978-0-323-89845-4.00007-2

Panarmasar N, Hinchiranan N, Kuchonthara P (2022) Catalytic hydrotreating of palm oil for bio-jet fuel production over Ni supported on mesoporous zeolite. Mater Today: Proc 57:1082–1087. https://doi.org/10.1016/j.matpr.2021.09.385

Pandit C, Banerjee S, Pandit S, Lahiri D, Kumar V, Chaubey KK, Al-Balushi R, Al-Bahry S, Joshi SJ (2023) Recent advances and challenges in the utilization of nanomaterials in transesterification for biodiesel production. Heliyon 9:e15475. https://doi.org/10.1016/j.heliyon.2023.e15475

Papadopoulos C, Kordouli E, Sygellou L, Bourikas K, Kordulis C, Lycourghiotis A (2021) W promoted Ni-Al_2O_3 co-precipitated catalysts for green diesel production. Fuel Process Technol 217:106820. https://doi.org/10.1016/j.fuproc.2021.106820

Patel M, Ayedun AO, Kumar A, Gupta R (2019) What is the production cost of renewable diesel from woody biomass and agricultural residue based on experimentation? A comparative assessment. Fuel Process Technol 191:79–92. https://doi.org/10.1016/j.fuproc.2019.03.026

Patra D, Patra BR, Pattnaik F, Hans N, Kushwaha A (2022) Recent evolution in green technologies for effective valorization of food and agricultural wastes. In: Hussain CM, Singh S, Goswami L (eds) Emerging Trends to Approaching Zero Waste: Environmental and Social Perspectives, 1st edn. Elsevier, pp 103–132. https://doi.org/10.1016/B978-0-323-85403-0.00001-3

Pavloviç S, Marinkovic D, Kostic M, Loncarevic D, Mojovic L, Stankovic M, Veljkovic V (2021) The chicken eggshell calcium oxide ultrasonically dispersed over lignite coal fly ash-based cancrinite zeolite support as a catalyst for biodiesel production. Fuel 289:119912. https://doi.org/10.1016/j.fuel.2020.119912

Permata M, Trisunaryanti W (2020) The effect of nickel content impregnated on zeolite toward catalytic activity and selectivity for hydrotreating of cashew nut shell liquid oil. Rasayan J Chem 13(1):772–779. https://doi.org/10.31788/RJC.2020.1315529

Pighinelli ALMT, Schaffer MA, Boateng AA (2018) Utilization of eucalyptus for electricity production in Brazil via fast pyrolysis: a techno-economic analysis. Renew Energy 119:590–597. https://doi.org/10.1016/j.renene.2017.12.036

Pinheiro AP, Arauzo J, Fonts I, Domine ME, Arroyo AF, Garcia-Perez ME, Montoya J, Chejne F, Pfromm P, Garcia-Perez M (2019) Challenges and opportunities for bio-oil refining: a review. Energy Fuels 33:4683–4720. https://doi.org/10.1021/acs.energyfuels.9b00039

Piñón-Muñiz M, Ramos-Sánchez V, Gutiérrez-Méndez N, Pérez-Vega S, Sacramento-Rivero J, Vargas-Consuelos CI, Martinez F, Graeve O, Orozco-Mena R, Quintero-Ramos A, Sánchez-Madrigal M, Salmerón I (2023) Potential use of Sotol bagasse (*Dasylirion* spp.) as a new biomass source for liquid biofuels production: comprehensive characterization and ABE fermentation. Renew Energy 212:632–643. https://doi.org/10.1016/j.renene.2023.05.055

Poudel J, Shah M, Karki J, Oh SC (2017) Qualitative analysis of transesterification of waste pig fat in supercritical alcohols. Energies 10:265. https://doi.org/10.3390/en10030265

Powar RS, Yadav AS, Ramakrishna CS, Patel S, Mohan M, Sakharwade SG, Choubey M, Ansu AK, Sharma A (2022) Algae: a potential feedstock for third generation. Mater Today. https://doi.org/10.1016/j.matpr.2022.07.161

Prabhu N, Karthikadevi S, Gajendran T (2021) Comprehensive review of the prospectives and development for the production of bioalcohols using nanoparticles. In: Kumar RP, Bharathiraja B (eds) Nanomaterials application in biofuels and bioenergy production systems, 1st edn. Academic Press, pp 379–391. https://doi.org/10.1016/B978-0-12-822401-4.00005-2

Prajapati P, Shrivastava S, Sharma V, Srivastava P, Shankhwar V, Sharma A, Srivastava SK, Agarwal DD (2023) Karanja seed shell: a sustainable green heterogeneous catalyst for biodiesel production. Results Eng 18:101063. https://doi.org/10.1016/j.rineng.2023.101063

Priya PS, Verma Y, Muhal RA, Goswami C, Singh T (2022) Biofuels: An alternative to conventional fuel and energy source. Mater Today 48:1178–1184. https://doi.org/10.1016/j.matpr.2021.08.227

Promsampao N, Chollacoop N, Pattiya A (2022) Effect of low-temperature hydrothermal treatment of HZSM-5 extrudates on the production of deeply-deoxygenated bio-oil via ex-situ catalytic fast pyrolysis of biomass. Fuel 324:124627. https://doi.org/10.1016/j.fuel.2022.124627

Pugazhendhi A, Mathimani T, Varjani S, Rene ER, Kumar G, Kim SH, Ponnusamy VK, Yoon JJ (2019) Biobutanol as a promising liquid fuel for the future—recent updates and perspectives. Fuel 253:637–646. https://doi.org/10.1016/j.fuel.2019.04.139

Puricelli S, Cardellini G, Casadei S, Faedo D, Oever AE, Grosso M (2021) A review on biofuels for light-duty vehicles in Europe. Renew Sustain Energy Rev 137:110398. https://doi.org/10.1016/j.rser.2020.110398

Pydimalla M, Husaini S, Kadire A, Verma RK (2023) Sustainable biodiesel: a comprehensive review on feedstock, production methods, applications, challenges and opportunities. Mater Today: Proc (in Press). https://doi.org/10.1016/j.matpr.2023.03.593

Quah RV, Tan YH, Mubarak NM, Khalid M, Abdullah EC, Nolasco-Hipolito C (2019) An overview of biodiesel production using recyclable biomass and non-biomass derived magnetic catalysts. J Environ Chem Eng 7(4):103219. https://doi.org/10.1016/j.jece.2019.103219

Quesada J, Faba L, Díaz E, Ordonez S (2018) Enhancement of the 1-butanol productivity in the ethanol condensation catalyzed by noble metal nanoparticles supported on Mg–Al mixed oxide. Appl Catal 563:64–72. https://doi.org/10.1016/j.apcata.2018.06.037

Rabiu SD, Auta M, Kovo AS (2018) An upgraded bio-oil produced from sugarcane bagasse via the use of HZSM-5 zeolite catalyst. Egypt J Pet 27:598–594. https://doi.org/10.1016/j.ejpe.2017.09.001

Rahimi Z, Anand A, Gautam S (2022) An overview on thermochemical conversion and potential evaluation of biofuels derived from agricultural wastes. Energy Nexus 7:100125. https://doi.org/10.1016/j.nexus.2022.100125

Rajendran N, Kang D, Han J, Gurunathan B (2022) Process optimization, economic and environmental analysis of biodiesel production from food waste using a citrus fruit peel biochar catalyst. J

Clean Prod 365:132712. https://doi.org/10.1016/j.clepro.2022.132712

Rambabu K, Bharath G, Sivarajasekar N, Velu S, Sudha PN, Wongsakulphasatch S, Banat F (2023) Sustainable production of bio-jet fuel and green gasoline from date palm seed oil via hydroprocessing over tantalum phosphate. Fuel 331:125688. https://doi.org/10.1016/j.fuel.2022.125688

Ramos A, Monteiro E, Rouboa A (2022) Biomass pretreatment techniques for the production of biofuels using thermal conversion methods—a review. Energy Convers Manage 270:116271. https://doi.org/10.1016/j.enconman.2022.116271

Rathnam VM, Madras G (2019) Conversion of *Shizochitrium limacinum* microalgae to biodiesel by non-catalytic transesterification using various supercritical fluids. Bioresour Technol 288:121538. https://doi.org/10.1016/j.biortech.2019.121538

Rathnam VM, Modak JM, Madras G (2020) Non-catalytic transesterification of dry microalgae to fatty acid ethyl esters using supercritical ethanol and ethyl acetate. Fuel 275:117998. https://doi.org/10.1016/j.fuel.2020.117998

Ravindran M, Asikin-Mijan N, Ong HC, Derawi D, Yusof M, Mastuli M, Lee H, Mahmood W, Razali M, Al-Sultan G, Tufiq-Yap Y (2022) Feasibility of advancing the production of bio-jet fuel via microwave reactor under low reaction temperature. J Anal Appl Pyrolysis 168:105772. https://doi.org/10.1016/j.jaap.2022.105772

Rempel A, Sossella F, Margarites A, Astolfi A, Steinmetz R, Kunz A, Treichel H, Colla L (2019) Bioethanol from Spirulina platensis biomass and the use of residuals to produce biomethane: an energy efficient approach. Bioresour Technol 288:121588. https://doi.org/10.1016/j.biortech.2019.121588

International Energy Agency (IEA) Renewables (2020) https://www.iea.org/reports/renewables/. Accessed 20 Oct 2020

Rezania S, Mahdinia S, Oryani B, Cho J, Kwon EE, Bozorgian A, Nodeh HR, Darajeh N, Mehranzamir K (2022) Biodiesel production from wild mustard (*Sinapis Arvensis*) seed oil using a novel heterogeneous catalyst of $LaTiO_3$ nanoparticles. Fuel 307:121759. https://doi.org/10.1016/j.fuel.2021.121759

Rico X, Yáñez R, Gullón B (2023) Evaluation of strategies for enhanced bioethanol production from melon peel waste. Fuel 334:126710. https://doi.org/10.1016/j.fuel.2022.126710

Ridwan I, Katsuragawa N, Tamura K (2020) Process optimization, reaction kinetics, and thermodynamics studies of water addition on supercritical methyl acetate for continuous biodiesel production. J Supercrit Fluids 166:105038. https://doi.org/10.1016/j.supflu.2020.105038

Rocha PD, Oliveira LS, Franca AS (2019) Sulfonated activated carbon from corn cobs as heterogeneous catalysts for biodiesel production using microwave-assisted transesterification. Renew Energy 143:1710–1716. https://doi.org/10.1016/j.renene.2019.05.070

Rodriguez Y, Guerra R, Vizuete K, Debut A, Stretwieser DA, Mora JR, Ponce S (2023) Kinetic study of the catalytic cracking of waste motor oil using biomass-derived heterogeneous catalysts. Waste Manage 167:46–54. https://doi.org/10.1016/j.wasman.2023.05.027

Roy M, Mohanty K (2021) Valorization of de-oiled microalgal biomass as a carbon-based heterogeneous catalyst for a sustainable biodiesel production. Bioresour Technol 337:125424. https://doi.org/10.1016/j.biortech.2021.125424

Rozina CSR, Ahmad M, Sultana S, Zafar M, Asif S, Bokhari A, Nomanbhay S, Mubashir M, Khoo KS, Show PL (2022) Green synthesis of biodiesel from Citrus medica seed oil using green nanoparticles of copper oxide. Fuel 323:124285. https://doi.org/10.1016/j.fuel.2022.124285

Ruangudomsakul M, Osakoo N, Wittayakun J, Keawkumay C, Butburee T, Youngjan S, Faungnawakij K, Poo-arporn Y, Kidkhunthod P, Khemthong P (2021) Hydrodeoxygenation of palm oil to green diesel products on mixed-phase nickel phosphides. Mol Catal 2021:111422. https://doi.org/10.1016/j.mcat.2021.111422

Rueangsan K, Sonsupap S, Promsampao N, Chollacoop N, Pattiya A (2023) Effect of condensation-assisted solid media on the production of bio-oil by fast pyrolysis of cassava residues in a free-fall reactor. J Energy Inst 107:101189. https://doi.org/10.1016/j.joei.2023.101189

Saetiao P, Kongrit N, Cheng C, Jitjamnong J, Direksilp C, Khantikulanon N (2023) Catalytic conversion of palm oil into sustainable biodiesel using rice straw ash supported-calcium oxide as a heterogeneous catalyst: Process simulation and techno-economic analysis. Case Studies Chem Environ Eng 8:100432. https://doi.org/10.1016/j.cscee.2023.100432

Safa-Gamal M, Asikin-Mijan N, Arumugam M, Khalit WN, Azreena IN, Hafez FS, Taufiq-Yap, (2021) Catalytic deoxygenation by H_2-free single-step conversion of free fatty acid feedstock over a Co–Ag carbon-based catalyst for green diesel production. J Anal Appl Pyrolysis 160:105334. https://doi.org/10.1016/j.jaap.2021.105334

Safaripour M, Saidi M, Moradi P (2023) Ex-situ biodiesel production from *Simmondsia chinensis* (Jojoba) biomass: process evaluation and optimization. J Ind Eng Chem 124:392–401. https://doi.org/10.1016/j.jiec.2023.04.033

Saidi M, Safaripour M, Ameri FA, Jomeh MR (2023) Application of sulfonated biochar-based magnetic catalyst for biodiesel production: sensitivity analysis and process optimization. Chem Eng Proc 190:109419. https://doi.org/10.1016/j.cep.2023.109419

Salafia F, Ferracane A, Tropea A (2022) Pineapple waste cell wall sugar fermentation by *Saccharomyces cerevisiae* for second generation bioethanol production. Fermentation 8:100. https://doi.org/10.3390/fermentation8030100

Sawaira M, Ahmad M, Munir M, Zafar M, Sultana S, Dawood S, Almohana AI, Hassan MH, Alharbi AF, Ahmad Z (2023) Efficient application of newly synthesized green Bi_2O_3 nanoparticles for sustainable biodiesel production via membrane reactor. Chemosphere 310:136838. https://doi.org/10.1016/j.chemosphere.2022.136838

Scaldaferri CA, Pasa VMD (2019a) Green diesel production from upgrading of cashew nut shell liquid. Renew Sustain Energy Rev 111:303–313. https://doi.org/10.1016/j.rser.2019.04.057

Scaldaferri CA, Pasa VMD (2019b) Production of jet fuel and green diesel range biohydrocarbons by hydroprocessing of soybean oil over niobium phosphate catalyst. Fuel 245:458–466. https://doi.org/10.1016/j.fuel.2019.01.179

Sentanuhady J, Hasan WH, Muflikhun MA (2022) Recent progress on the implementation of renewable biodiesel fuel for automotive and power plants: raw materials perspective. Adv Mater Sci Eng 2022:1–19. https://doi.org/10.1155/2022/5452942

Shahbeik H, Peng W, Panahi H, Dehhaghi M, Guillemin G, Fallahi A, Amiri H, Rehan M, Raikwar D, Latine H, Pandalone B, Khoshnevisan B, Sonne C, Vaccaro L, Nizami AS, Gupta V, Lam S, Pan J, Luque R, Sels B, Tabatabaei M, Aghbashlo M (2022) Synthesis of liquid biofuels from biomass by hydrothermal gasification: a critical review. Renew Sustain Energy Rev 167:112833. https://doi.org/10.1016/j.rser.2022.112833

Sharma A, Kodgire P, Kachhwaha SS (2020) Investigation of ultrasound-assisted KOH and CaO catalyzed transesterification for biodiesel production from waste cotton-seed cooking oil: process optimization and conversion rate evaluation. J Clean Prod 259:120982. https://doi.org/10.1016/j.rser.2019.109394

Shen Z, Zhang K, Ao Z, Ma L, Duan J (2018) Evaluation of biodiesel from *Xanthoceras sorbifolia* Bunge seed kernel oil from 13 areas in China. J for Res 30:869–877. https://doi.org/10.1007/s11676-018-0683-9

Shiamala L, Vignesh K, Ali BMJ (2023) Sunlight active TiO_2-Bi_2WO_6 photocatalyst pretreatment of biomass for simultaneous hydrolysis and saccharification in bioethanol production. Fuel 333:126332. https://doi.org/10.1016/j.fuel.2022.126332

Shobana R, Vijayalakshmi S, Deepanraj B, Ranjitha J (2021) Biodiesel production from *Capparis spinosa* L. seed oil using calcium oxide as a heterogeneous catalyst derived from oyster shell. Mater Today: Proc 80:3216–3220. https://doi.org/10.1016/j.matpr.2021.07.215

Si W, Li Y, Zheng J, Wei S, Wang D (2017) Enhanced hydrolysis of bamboo biomass by chitosan based solid acid catalyst with surfactant addition in ionic liquid. Carbohyd Polym 174:154–159. https://doi.org/10.1016/j.carbpol.2017.05.082

Silva CM, Oliveira AC, Rocha B, Gusmao C, Freitas L, Alves M, Guimaraes A, Lelis W (2018) Biomass torrefaction for energy purposes—definitions and an overview of challenges and opportunities in Brazil. Renew Sustain Energy Rev 82:2426–2432. https://doi.org/10.1016/j.rser.2017.08.095

Singh N, Dhanya BS, Verma ML (2020) Nano-immobilized biocatalysts and their potential biotechnological applications in bioenergy production. Mater Sci Energy Technol 3:808–824. https://doi.org/10.1016/j.mset.2020.09.006

Singh AR, Singh SK, Jain S (2022) A review on bioenergy and biofuel production. Mater Today: Proc 49:510–516. https://doi.org/10.1016/j.matpr.2021.03.212

Singh Y, Singh D, Singh NK, Sharma A, Rahim EA, Ranganathan A, Palanichamy P, Palamanit A, Kumar S (2023) Production of bio-oil from lychee-based biomass through pyrolysis and maximization of bio-oil yield with statistical and machine learning techniques. J Clean Prod 413:137472. https://doi.org/10.1016/j.jclepro.2023.137472

Siqueira MR, Perrone OM, Metzker G, Oliveira DC, Thomeo J, Boscolo M (2019) Highly selective 1-butanol obtained from ethanol catalyzed by mixed metal oxides: reaction optimization and catalyst structure behavior. Mol Catal 476:110516. https://doi.org/10.1016/j.mcat.2019.110516

Sitepu E, Heimann K, Raston C, Zhang W (2020) Critical evaluation of process parameters for direct biodiesel production from diverse feedstock. Renew Sustain Energy Rev 123:109762. https://doi.org/10.1016/j.rser.2020.109762

Skrotskyi S, Voychuk S, Khomenko L, Vasyliuk O, Pidgorskyi V (2019) Influence of nanoparticles on the solventogenesis of bacteria *Clostridium beijerinckii* IMV B-7806, clostridium acetobutylicum IMV B-7807. Ukrainian Food J 8(1):110–118. https://doi.org/10.24263/2304-974X-2019-8-1-12

Smuga-Kogut M, Piskier T, Walendzik B, Szymanowska-Powałowska D (2019) Assessment of wasteland derived biomass for bioethanol production. Electron J Biotechnol 41:1–8. https://doi.org/10.1016/j.ejbt.2019.05.001

Sreeharsha RV, Dubey N, Mohan SV (2023) Orienting biodiesel production towards sustainability and circularity by tailoring the feedstock and process—review. J Clean Prod 414:137526. https://doi.org/10.1016/j.jclepro.2023.137526

Srivastava RK (2019) Bio-energy production by contribution of effective and suitable microbial system. Mater Sci Energy Technol 2:308–318. https://doi.org/10.1016/j.mset.2018.12.007

Sudhakar M, Ravel M, Perumal K (2021) Pretreatment and process optimization of bioethanol production from spent biomass of *Ganoderma lucidum* using *Saccharomyces cerevisiae*. Fuel 306:121680. https://doi.org/10.1016/j.fuel.2021.121680

Supang W, Ngamprasertsith S, Sakdasri W, Sawangkeaw R (2022) Ethyl acetate as extracting solvent and reactant for producing biodiesel from spent coffee grounds: a catalyst—and glycerol—free process. J Supercrit Fluids 186:105586. https://doi.org/10.1016/j.supflu.2022.105586

Suwannasom P, Tansupo P, Ruangviriyachai C (2016) A bone-based catalyst for biodiesel production from waste cooking oil. Energy Sour A Recov Util Environ 38:3167–3173. https://doi.org/10.1080/15567036.2015.1137998

Tahir MH, Mubashir T, Hussain MB, Cheng X, Karim A, Ali N, Jamil M, Khan AM, Irfan RM (2021) Selective catalytic conversion of tea waste biomass into phenolic-rich bio-oil and subsequent extraction. J Anal Appl Pyrolysis 159:105315. https://doi.org/10.1016/j.jaap.2021.105315

Tekin N, Karatay SE, Dönmez G (2023) Optimization studies about efficient biobutanol production from industrial tea waste by *Clostridium beijerinckii*. Fuel 331:125763. https://doi.org/10.1016/j.fuel.2022.125763

Tran QK, Le ML, Ly HV, Woo HC, Kim J, Kim SS (2021) Fast pyrolysis of pitch pine biomass in a bubbling fluidized-bed reactor for bio-oil production. J Ind Eng Chem 98:168–179. https://doi.org/10.1016/j.jiec.2021.04.005

Trentini C, Postaue N, Cardozo-Filho L, Reis R, Sampaio SC, Silva C (2019) Production of esters from grease trap waste lipids under supercritical conditions: effect of water addition on ethanol. J Supercrit Fluids 47:9–16. https://doi.org/10.1016/j.supflu.2019.02.008

Tsolcha ON, Patrinou V, Economou CN, Dourou M, Aggelis G, Tekerlekopoulou AG (2021) Utilization of biomass derived from cyanobacteria-based agro-industrial wastewater treatment and raisin residue extract for bioethanol production. Water 13:486. https://doi.org/10.3390/w13040486

UNNews (2021) Wasting food just feeds climate change, new UN environment report warns. In: UNNews Global perspective human stories. https://news.un.org/en/story/2021/03/1086402. Accessed 15 Jun 2023

Vamvuka D (2011) Bio-oil, solid and gaseous biofuels from biomass pyrolysis processes—an overview. Inter J Energy Res 35(10):835–862. https://doi.org/10.1002/er.1804

van Schalkwyk DL, Mandegari M, Farzad S, G¨orgens JF, (2020) Techno-economic and environmental analysis of bio-oil production from forest residues via noncatalytic and catalytic pyrolysis processes. Energy Convers Manag 213:112815. https://doi.org/10.1016/j.enconman.2020.112815

Vasco-Correa GX, Li Y (2016) Biological pretreatment of lignocellulosic biomass. In: Mussatto SI (ed) Biomass fractionation technologies for a lignocellulosic feedstock based biorefinery, 1st edn. Elsevier, pp 561–585. https://doi.org/10.1016/B978-0-12-802323-5.00024-4

Vaskalis I, Skoulou V, Stavropoulos G, Zabaniotou A (2019) Towards circular economy solutions for the management of rice processing residues to bioenergy via gasification. Sustainability 11:6433. https://doi.org/10.3390/su11226433

Vassilev SV, Baxter D, Andersen LK, Vassileva CG, Morgan TJ (2012) An overview of the organic and inorganic phase composition of biomass. Fuel 94:1–33. https://doi.org/10.1016/j.fuel.2011.09.030

Vázquez-Garrido I, López-Benítez A, Guevara-Lara A, Berhault G (2021) Synthesis of NiMo catalysts supported on Mn–Al_2O_3 for obtaining green diesel from waste soybean oil. Catal Today 365:327–140. https://doi.org/10.1016/j.cattod.2020.06.001

Vellaiyan S (2020) Enhancement in combustion, performance, and emission characteristics of a biodiesel-fueled diesel engine by using water emulsion and nanoadditive. Renew Energy 145:2108–2120. https://doi.org/10.1016/j.renene.2019.07.140

Velusamy K, Devanand J, Kumar PS, Soundarajan K, Sivasubramanian V, Sindhu J, Vo DV (2021) A review on nano-catalysts and biochar-based catalysts for biofuel production. Fuel 306:121632. https://doi.org/10.1016/j.fuel.2021.121632

Verma N, Kumar V, Bansal M (2012) Utilization of egg shell waste in cellulase production by *Neurospora crassa* under wheat bran-based solid state fermentation. Pol J Environ Stud 21:491–497

Wakatuntu J, Olupot PW, Jjagwe J, Menya E, Okure M (2023) Optimization of pyrolysis conditions for production of rice husk-based bio-oil as an energy carrier. Results Eng 17:100947. https://doi.org/10.1016/j.rineng.2023.100947

Wang H, Wang G, Qi J, Schandl H, Li Y, Feng C, Yang X, Wang Y, Wang X, Liang S (2020) Scarcity-weighted fossil fuel footprint of China at the provincial level. Appl Energy 258:114081. https://doi.org/10.1016/j.apenergy.2019.114081

Wang J, Jiang J, Li D, Meng X, Zhan G, Wang Y, Zhang A, Sun Y, Ruan R, Ragauskas (2022a) Creating values from wastes: producing biofuels from waste cooking oil via a tandem vapor-phase hydrotreating process. Appl Energy 323:119629. https://doi.org/10.1016/j.apenergy.2022.119629

Wang J, Jiang J, Zhang Z, Meng X, Sun Y, Ragauskas AJ, Zhang Q, Tsang DCW (2022b) Converting polyisoprene rubbers into bio-jet fuels via a cascade hydropyrolysis and vapor-phase hydrogenation process. Energy Convers Manage 270:116250. https://doi.org/10.1016/j.enconman.2022.116250

Wang W, Fan W, Zhou P (2022c) Evolution of global fossil fuel trade dependencies. Energy 238:121924. https://doi.org/10.1016/j.energy.2021.121924

Wei H, Liu W, Chen X, Yang Q, Li J, Chen H (2019) Renewable bio-jet fuel production for aviation: a review. Fuel 254:115599. https://doi.org/10.1016/j.fuel.2019.06.007

Wei W, Wu J, Shao Q, Yu Z, Yu H, Zhao G (2022) Biodiesel production using a biomass-based solid acid catalyst synthesized from agricultural residue garlic peel. Waste Biomass Valor 13:3597–3609. https://doi.org/10.1007/s12649-022-01742-9

Why E, Ong H, Lee H, Chen W, Asikin-Mijan N, Varman M (2021) Conversion of bio-jet fuel from palm kernel oil and its blending effect with jet A-1 fuel. Energy Convers Manage 243:114311. https://doi.org/10.1016/j.enconman.2021.114311

Wu Y, Wang Z, Ma X, Xue C (2021) High temperature simultaneous saccharification and fermentation of corn stover for efficient butanol production by a thermotolerant *Clostridium acetobutylicum*. Process Biochem 100:20–25. https://doi.org/10.1016/j.procbio.2020.09.026

Wu Y, Xia C, Cao J, Garalleh HA, Garaleh M, Khouj M, Pugazhendhi A (2023) A review on current scenario of nanocatalysts in biofuel production and potential of organic and inorganic nanoparticles in biohydrogen production. Fuel 338:127216. https://doi.org/10.1016/j.fuel.2022.127216

Xiang C, Liu S, Fu Y, Chang J (2019) A quick method for producing biodiesel from soy sauce residue under supercritical carbon dioxide. Renew Energy 134:739–744. https://doi.org/10.1016/j.renene.2018.11.059

Xiong M, Huang J, He X, Zhou Z, Qu X, Faisal S, Abomohra A (2023) Evaluation of bio-oil/biodiesel production from co-pyrolysis of corn straw and natural hair: a new insight towards energy recovery and waste biorefinery. Fuel 331:125710. https://doi.org/10.1016/j.fuel.2022.125710

Xue X, Liu J, Xia D, Liang J (2023) Hydrocarbon-rich bio-oil production from the coupling formaldehyde-pretreatment and catalytic pyrolysis of poplar sawdust. Biomass Bioenergy 173:106807. https://doi.org/10.1016/j.biombioe.2023.106807

Yatish KV, Prakash RM, Ningaraju C, Sakar M, Balakrishna RG, Lalithamba HS (2021) Terminalia chebula as a novel green source for the synthesis of copper oxide nanoparticles and as feedstock for biodiesel production and its application on diesel engine. Energy 215:119165. https://doi.org/10.1016/j.energy.2020.119165

Yenumala SR, Kumar P, Maity SK, Shee D (2019) Production of green diesel from karanja oil (*Pongamia pinnata*) using mesoporous NiMo-alumina composite catalysts. Bioresour Technol Rep 7:100288. https://doi.org/10.1016/j.biteb.2019.100288

Yuan C, Abomohra AE, Wang S, Liu Q, Zhao S, Cao B, Hu X, Marrakchi F, He Z, Hu Y (2021) High-grade biofuel production from catalytic pyrolysis of waste clay oil using modified activated seaweed carbon-based catalyst. J Clean Prod 313:127928. https://doi.org/10.1016/j.jclepro.2021.127928

Yubao C, Yajie H, Yongyan Z, Liming Z, Shunping Y, Yanni G, Jiangli M, Junchen D, Souliyathai D, Aimin Z (2017) Converting rubber seed oil into hydrocarbon fuels via supported Pd-catalyst. Int J Agric Biol Eng 10(6):201–209. https://doi.org/10.25165/j.ijabe.20171006.2742

Yulia D, Zulys A (2020) Hydroprocessing of kemiri sunan oil (reutealis trisperma (blanco) airy shaw) over NiMoCe/γ-Al_2O_3 catalyst to produce green diesel. IOP Confer Ser Mater Sci Eng 763:012038. https://doi.org/10.1088/1757-899X/763/1/012038

Yuliana M, Santoso S, Soetaredjo F, Ismadji S, Ayucitra A, Angkawijaya A, Ju Y, Tran-Nguyen P (2020) A one-pot synthesis of biodiesel from leather tanning waste using supercritical ethanol: process optimization. Biomass Bioenergy 142:105761. https://doi.org/10.1016/j.biombioe.2020.105761

Yusuf AA, Inambao F (2019) Bioethanol production from different *Matooke* peels species: a surprising source for alternative fuel. Case Stud Therm Eng 13:100357. https://doi.org/10.1016/j.csite.2018.11.008

Zanivan J, Bonatto C, Scapini T, Dalastra C, Bazoti SF, Júnior S, Fongaro G, Treichel H (2022) Evaluation of bioetanol production from a mixed fruit waste by *Wickerhamomyces* sp. UFFS-CE-3.1.2. BioEnergy Res 15:175–182. https://doi.org/10.1007/s12155-021-10273-5

Zarchin R, Rabaev M, Vidruk-Nehemya R, Landau MV, Herskowitz M (2015) Hydroprocessing of soybean oil on nickel-phosphide supported catalysts. Fuel 139:684–691. https://doi.org/10.1016/j.fuel.2014.09.053

Zeng Z, Tian X, Wang Y, Cui X, Zhang Q, Dai L, Liu Y, Zou R, Chen J, Liu J, Ruan R (2021) Microwave-assisted catalytic pyrolysis of corncobs with Fe-modified *Choerospondias axillari* seed-based biochar catalyst for phenol-rich bio-oil. J Anal Appl Pyrolysis 159:105306. https://doi.org/10.1016/j.jaap.2021.105306

Zhang X (2016) Essential scientific mapping of the value chain of thermochemically converted second-generation bio-fuels. Green Chem 18(19):5086–5117. https://doi.org/10.1039/C6GC02335E

Zhang Y, Duan D, Lei H, Villota E, Ruan R (2019) Jet fuel production from waste plastics via catalytic pyrolysis with activated carbons. Appl Energy 251:113337. https://doi.org/10.1016/j.apenergy.2019.113337

Zhang J, Cai D, Qin Y, Liu D, Zhao X (2020a) High value-added monomer chemicals and functional bio-based materials derived from polymeric components of lignocellulose by organosolv fractionation. Biofuels Bioprod Bioref 14(2):371–401. https://doi.org/10.1002/bbb.2057

Zhang Y, Niu S, Lu C, Gong Z, Hu X (2020b) Catalytic performance of $NaAlO_2$/γ-Al_2O_3 as heterogeneous nanocatalyst for biodiesel production: optimization using response surface methodology. Energy Convers Manage 203:112263. https://doi.org/10.1016/j.enconman.2019.112263

Zhang M, Hu Y, Wang H, Li H, Han X, Zeng Y, Xu CC (2021) A review of bio-oil upgrading by catalytic hydrotreatment: advances, challenges, and prospects. Mol Catal 504:111438. https://doi.org/10.1016/j.mcat.2021.111438

Zhang Y, Wang J, Wei J, Yang Y, Lv Peng SuW, Bai Y, Song X, Yu G (2023) Biomass catalytic pyrolysis over CaO microspheres: relationship between the production of bio-oil components and CO_2 capture. Fuel Process Technol 247:107775. https://doi.org/10.1016/j.fuproc.2023.107775

Zhao J, Cao JP, Wei F, Zhao X, Feng X, Huang X, Zhao M, Wei X (2019) Sulfation-acidified HZSM-5 catalyst for in-situ catalytic conversion of lignite pyrolysis volatiles to light aromatics. Fuel 255:115784. https://doi.org/10.1016/j.fuel.2019.115784

Zheng Y, Wang J, Li D, Liu C, Lu Y, Lin X, Zheng Z (2021) Highly efficient catalytic pyrolysis of biomass vapors upgraded into jet fuel range hydrocarbon-rich bio-oil over a bimetallic Pt-Ni/γ-Al_2O_3 catalyst. Int J Hydrog Energy 46:27922–27940. https://doi.org/10.1016/j.ijhydene.2021.06.082

Zou R, Qian M, Wang C, Mateo W, Wang Y, Dai L, Lin X, Zhao Y, Huo E, Wang L, Zhang X, Kong X, Ruan R, Lei H (2022) Biochar: From by-products of agro-industrial lignocellulosic waste to tailored carbon-based catalysts for biomass thermochemical conversions. J Chem Eng 441:135972. https://doi.org/10.1016/j.cej.2022.135972

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