Chapter 2
Novel Feedstocks for Biofuels: Current Scenario and Recent Advancements

Zaira Khalid, Shahrukh Nawaj Alam, Abhishek Guldhe, and Bhaskar Singh

Abstract New policy initiatives combined with rise in demand for transport fuel have stimulated an increase in biofuel production throughout the world. Since the beginning of bioenergy era, biofuel industries have been mostly dependent on feedstocks with agricultural importance especially for production of bioethanol and biodiesel. The main problem of conventional feedstocks such as edible crops or oilseeds lies with the availability, demand and the cultivation of raw material which may impact food production. Moreover, they require large arable land masses and irrigation facilities giving rise to secondary problems such as high water requirement leading to increase in production cost. Therefore, the current situation demands such raw material for biofuel production that can overcome food versus fuel scenario and water dependency. Various novel feedstocks like lignocellulosic waste, municipal wastes, waste oils, sewage waste, non-edible oil seeds, forest residues, microalgae, aquatic weeds and others which can be used to overcome aforesaid issues and reduce the production cost have been mentioned in this chapter.

Keywords Bioenergy · Biofuel · Conventional feedstocks · Novel feedstocks

2.1 Introduction

The potential of biofuel as an alternative to fossil fuel is immense which has led to commercial production of biofuel for reduction in carbon emission (Paul et al. 2019). New policy initiatives combined with rise in demand for transport fuel have stimulated increase in biofuel production throughout the world. Adoption of mandates by countries has increased regarding the consumption of biofuels produced domestically for energy security and improvement of air quality (IEA 2018). Predominantly,

---

Z. Khalid · S. N. Alam · B. Singh (✉)
Department of Environmental Sciences, Central University of Jharkhand, Ranchi, India
e-mail: bhaskar.singh@cuj.ac.in

A. Guldhe
Amity Institute of Biotechnology, Amity University Maharashtra, Mumbai, India

A. Guldhe, B. Singh (eds.), *Novel Feedstocks for Biofuels Production*, Clean Energy Production Technologies, https://doi.org/10.1007/978-981-19-3582-4_2

biofuels are obtained from renewable photosynthetic matters such as biomass, micro- and macroalgae and various vascular plants. The primary products of biofuels can be in solid, liquid or gaseous forms like burning pellets, or other forms of liquid and gaseous biofuels but can be converted to other forms using various physical, chemical and thermal techniques (Rodionova et al. 2017). However, the main problem with conventional feedstocks lies with the availability and demand. The cultivation of raw material requires large arable land masses and irrigation facilities giving rise to secondary problems like food shortage and high water requirement. Therefore, the current scenario demands such raw material for biofuel production that can overcome 'food versus fuel' and water dependency. As a result, researchers, energy sector and policy makers are showing great interest in searching novel feedstock that can overcome aforesaid problems. Considerable research is currently being held in the field of identifying raw materials that can be supplied continuously without competing with food crops, optimizing and advancing conversion techniques to gain more output and reducing the overall cost of production keeping in view the environmental aspects. Emphasis is being given on waste materials such as lignocellulosic waste, municipal wastes, waste oils, sewage waste, non-edible oil seeds, forest residues, microalgae, aquatic weeds and other biomass which are showing great potential for the production of biofuels (Alam et al. 2021; Vasić et al. 2021). This chapter discusses current scenario of the biofuel production from novel feedstocks.

2.2 Biofuels

Biofuels may be described as liquid fuels derived from biomass used for transportation as an alternate to fossil fuel, including bioethanol derived from sugar, starch and lignocellulosic feedstocks, and biodiesel derived from oils and fats. According to the EASAC (2012) report, biofuels can be classified as first-, second- and third-generation biofuel that is primarily based on the origin or the raw materials from which they are extracted from such as biomass, waste materials or cultivated algae, whereas the concept of fourth-generation and fifth-generation biofuel is still at the elementary level of research. Biofuels of any generation are mainly derived from cellulose, hemicellulose, sugar, starch vegetable and animal fats. However, the general structure of biofuel doesn't change with the change in biofuel generation.

2.2.1 First-Generation Biofuels

First-generation biofuels consist of edible feedstocks or food crops such as corn, sugarcane, wheat, soya bean, rapeseed, coconut, palm, mustard, olive and others. The uses of food crops were quite popular for the production of biofuel in the beginning. High cost, competitiveness with food supplies and requirement of extensive growth conditions created problems at the beginning of biodiesel era. Availability of crops and comparatively easy conversion procedure are the main benefits of the first-generation feedstocks. The risk of competing with arable land and food supply, high cost of production and requirement of extensive growth conditions were the main disadvantages in the use of these feedstocks that increase the cost of food products creating ethical and sustainability issues (Gerbens-Leenes 2017). These drawbacks pushed researchers and policy makers to shift onto the different alternate sources for biofuel production (Tariq et al. 2012).

2.2.2 Second-Generation Biofuels

Drawbacks associated with first-generation biofuel feedstocks attracted researchers to work on non-edible feedstocks such as forest or waste-derived lignocellulosic biomass (LCB). The main advantages of these feedstocks apart from their no food value are minimal environmental impact and not requiring surplus amounts of fertilizer or water. The most prominent second-generation feedstocks include forest-derived lignocelluloses like switchgrass, miscanthus, Indian grass seed crops like jatropha, camelina, palm and rapeseed, waste cooking oil and municipal solid waste (Shi et al. 2009; Pandey et al. 2012; Ho et al. 2014; Bharti et al. 2020).

The main disadvantages of second-generation fuels are that the yield of many important non-edible plants like jatropha, jojoba and Karanja are not of the required value to compete with fossil fuels. However, these plants can be cultivated in nonarable and degraded lands. This being the main reason directly influences the economy of society without hampering the food production. The second-generation biofuel feedstock's carbon footprint is much lower than fossil fuels (Naik et al. 2010); however, requirement of alcohol in large quantity during the production process is one of the main drawbacks of second-generation biodiesel (Tariq et al. 2012).

2.2.3 Third-Generation Biofuels

First- and second-generation biofuels due to their various limitations demanded exploration of alternative raw materials for the production of biofuels superior to their predecessors. This led to the explorations of algal biomass for the third generation of biofuel. Both microalgae and macroalgae have been greatly explored owing to their high lipid content producing larger quantity of biofuel or indirectly as feedstock biogas production through fermentation in shorter period of time. They can convert light and carbon dioxide into various chemical compounds through cellular activities like carbohydrate, lipid, protein, vitamin, etc. that can be utilized in health, food supplement, energy and pharmaceutical industry (Costa and De Morais 2011). The advantages of third-generation biofuel feedstock include high growth rate and productivity much higher than terrestrial plants that can be harvested in just 5–6 days after cultivation, high carbon sequestering potential, higher amount of oil percentage and lesser influence on food supply. The main disadvantages of third-generation biofuels are requirement of large investment, surplus amount of sunlight and difficulties in oil production (Liew et al. 2014; Lamichhane et al. 2021).

2.2.4 Fourth-Generation Biofuels

Fourth-generation biofuels are derived by genetically modifying microorganisms to enhance quality and productivity. These microorganisms are modified to increase intake of carbon dioxide for photosynthesis, creating an enhanced carbon sink to enhance the overall growth. Some of the examples include *Phaeodactylum tricornutum* sp., *Chlamydomonas reinhardtii* sp., *Chlorella vulgaris*, *Thalassiosira pseudonana* sp., etc. which have been modified genetically to enhance the adaptability and growth rate to increase the production and hence biofuel (Illman et al. 2000; Rizwan et al. 2017; Abdullah et al. 2019).

The genetically modified microorganisms and their environmental advantages may include higher carbon dioxide sequestration and assimilation, the reduction of GHGs and higher nutrient accumulation as well as nutrient tolerance making them suitable for wastewater treatment (Zhu et al. 2017; Leong et al. 2019). Some microorganisms and their modifications which have been reported in a few studies are shown in Table 2.1.

Table 2.1 Modifications in microorganisms

Microorganism specie	Modification result	Reference
Chlamydomonas reinhardtii	Two-fold increase in starch content and 2.4-fold higher accumulation of TAG	Rengel et al. (2018)
Chlamydomonas reinhardtii	Increased productivity and 28.5% increase in lipid content	Kao and Ng (2017)
Chlamydomonas reinhardtii	56% increase in total lipid	Tan and Lee (2017)
Chlorella sorokiniana and *Chlorella vulgaris*	2.2-fold increase in lipid accumulation	Lin et al. (2018)
Chlorella vulgaris	Increased productivity and 67% increase in lipid content	Sarayloo et al. (2018)
Phaeodactylum tricornutum	2.4-fold increase in lipid content	Xue et al. (2017)
Nannochloropsis salina	Biomass productivity increased 2.4 fold	Vikramathithan et al. (2020)
Thalassiosira pseudonana	Three-fold increase in lipid content	Trentacoste et al. (2013)
Synechococcus elongatus	41% increase in carbon uptake	Chen et al. (2012)
Chlamydomonas reinhardtii	50% increase in photosynthetic efficiency	Beckmann et al. (2009)

2.3 Types of Biofuels

With the reference to the source and feedstock, biofuels may be categorized into two types: primary and secondary biofuels. Primary biofuels are obtained from the raw material which can be applied in the biofuel production process in their natural/raw form without needing any types of pretreatment or processing and are used to produce heat and electricity. Some examples of primary biofuels include firewood, animal waste, crop waste, etc. Secondary biofuels are generated from processed waste or biomass and are converted into desired product by using various physical, chemical and biological means. The first generation of biofuels is the production of ethanol from starch. Biofuel can be further classified based on the state, nature and raw material into bioethanol, biodiesel and biogas.

2.3.1 Bioethanol

Bioethanol are alcohols produced by fermentation of simple sugar, carbohydrate or starch from crops such as maize, sugarcane, sorghum, soya bean, corn, etc. (Kumar et al. 2018). Bioethanol are largest produced liquid biofuel used in transportation industry as eco-friendly alternative to fossil fuel. Ethanol in its purest form possess relatively low energy density and poor storage characteristics and are therefore mostly used as additives in the blend of gasoline to enhance the energy density and octane number and reduce vehicle emission (Goldemberg and Teixeira Coelho 2004; Radakovits et al. 2010). Cellulose-based biomass can be utilized as effective feedstock to produce bioethanol, and several additions in the field of pretreatment and microorganism-assisted fermentation have been adopted to enhance the production process (Fatma et al. 2021).

2.3.2 Biodiesel

Biodiesel are produced from fats and oils from plant and animal origin through the process of esterification and transesterification. Biodiesel is the second largest liquid fuel utilized and produced after bioethanol used by transportation sector as a blend with fossil fuel in any kind of biodiesel engine. Biodiesel are mostly used as blends as the pure biodiesel burning may add up to NOx emissions and also cause problems during winter due to low viscosity leading to performance and maintenance issues (Ferreira et al. 2009). However, in blend it minimizes the emission of hydrocarbon and particles (Fisher et al. 1995).

2.3.3 Biogas

Biogas are obtained by fermenting organic feedstock with the help of anaerobic microorganisms. Biogas is regarded as one of the cleanest burning biofuel from a wide range of raw material. The most prominent advantage of biogas includes possibility of liquefaction, hence enhancing the storage capacity and transportation and can be supplied by same pipelines used to supply natural gas (Urban 2013). It is also easy to make without any complications and therefore can be produced even by farmers by using available raw materials like cow dung. The by-product after the extraction of biogas can be used again as fertilizer.

2.4 Biofuel Production from Various Novel Feedstocks

The search for novel feedstock that is environmentally and economically better than its predecessors has been a major research area since the first attempts at biofuel production. Currently, the major focus is on the biofuel feedstocks that are readily available, do not impact the global environment and are preferable if they assist in carbon reduction, can achieve multiple outputs or otherwise are not a nuisance to society; thus, biofuel production provides a mode of management. In current time, biofuel production from lignocellulose-based feedstock such as non-edible feedstocks, waste materials, algae, weeds both terrestrial and aquatic, etc. is in momentum and shows great potential for reducing fossil fuel dependency in the future.

2.4.1 Biofuel Production Using Biomass and Lignocellulose-Based Feedstocks

Lignocellulosic biomass is one of the most attractive feedstocks for biofuel production mainly due to its high energy content and renewable and inexpensive nature. Lignocellulose-based feedstocks are predominant in cellulose (33–55 wt%), hemicelluloses (20–40 wt%) and lignin (10–25 wt%) along with several kinds of extractives such as flavonoids, terpenoids, steroids, fats, carbohydrates and lipids which can be converted to various types of biofuels (Nanda et al. 2013). Most researches related to the utilization of lignocellulosic feedstocks for biofuel production focus on the biomasses which are considered waste in some regard or residues from other mainstream human activities such as agriculture, forestry, industrial domestic, etc. The main advantage of these kinds of feedstock includes elimination of food versus fuel competition faced by biofuel production system mainly concerning dilemma of fuel over food from land utilization. Most of the lignocellulosic wastes, in the present time, either end up in landfills, burnt or get discarded in waterbodies. Therefore, the effective utilization of these waste materials for the production of biofuel can lead to several environmental impacts such as decreasing waste pollution and decreasing GHG emission, thus called the next-generation biofuel feedstock. Some of the lignocellulosic feedstocks currently being utilized for the production of biofuel are mentioned below.

2.4.1.1 Non-edible Forest Products

Non-edible forest products and forestry residues represent a massive source of readily available biomass not needing additional land and other resources for biofuel production. These can be obtained from the by-products of raw material which are planted, processed and consumed. It is estimated that throughout the world around 501 million dry tonnes of forestry residues are generated every year (IEA 2010). These include non-consumable forest residues which are the second-largest lignocellulosic biomass source after agricultural residues. Forest products generally refer to non-edible or sometimes toxic fruits and seeds, parts of trees and low wood value species which can be important sources of LCB (lignocellulosic biomass) and utilized in the production of bioenergy. Forestry residues are mainly generated during and after logging and pruning operations and during the processing of woods in industries. Forestry residues can be found in a considerable amount for the production of bioenergy in the regions with large forest covers and high industrial use of wood. These types of forest residues may include woodchips, barks, hardwoods and sawdust which are utilized to produce burning pellets, pyrolysis oil, liquid biofuels, etc. Ren et al. (2012) studied the microwave pyrolysis of Douglas fir sawdust pellet and showed the highest bio-oil conversion of 57.8%. Similarly, Heo et al. (2010) studied furniture sawdust bio-oil production using a fluidized bed pyrolysis reactor and found the highest bio-oil conversion of 65%, whereas ethanol production from sawdust was studied by Tulashie et al. (2021) where they studied different acid hydrolysis for the conversion of substrate to bioethanol and found the production to be as high as 80%. Wood chips and pruning residues like barks also possess great biofuel potential which have been studied by researchers like Chukwuneke et al. (2019) where they analysed mahogany wood pyrolysis to produce bio-oil and found the maximum bio-oil yield to be 69.5 wt%.

Non-edible forest products include non-edible seed oils. These seeds may contain some harmful compounds and therefore may be unfit for human consumption; however, they can be successfully applied for the production of biofuels overcoming the economic, environmental and food versus fuel problems. The oil extracted from these non-edible seeds is mostly applied to produce biodiesel due to its liquid nature, higher combustion efficiency, lower sulphur content, easy availability and appropriate aromatic content (Shikha and Chauhan 2012). Also, it can help the competitiveness of biodiesel in price when compared to the biodiesel production from edible vegetable oils. A detailed description of the non-edible seed oil is discussed later in the chapter.

2.4.1.2 Aquatic Weeds

Aquatic weeds are nuisance causing plants that grow in water interfering with the intended use of water harming the environment and human welfare (Dhadse et al. 2021). Some aquatic biomasses such as *Eichhornia crassipes* (water hyacinth), *Pistia stratiotes* (water lettuce), *Salvinia molesta* (water fern) and *Lemna minor* (duckweed) have very high reproductive and doubling rate and invaded freshwater ecosystem completely taking over the waterbody causing considerable socio-economic problems (Alam et al. 2021). These aquatic weeds greatly affect the water quality and biodiversity throughout the world but owing to their unique physicochemical characteristics can be effectively used to produce several types of biofuel. Aquatic weeds also possess the ability to surpass other kinds of biofuels owing to their high reproductive rate. Other than that, aquatic weeds have a notable amount of cellulose, hemicellulose, lignin, carbohydrate, sugar, etc. which are essentially converted to several kinds of biofuels. Sugar undergoes direct fermentation to produce bioethanol; lignin parts are utilized to produce bio-oil, heat energy and combustible gases through thermochemical conversion. Aquatic weed also possesses lipids which are essentially made up of modified fatty acids which are converted into biodiesel through the process of transesterification (Naik et al. 2010). This biomass can also be utilized to produce liquid biofuel like biomethanol, biobutanol and gaseous biofuels like biohydrogen using biological conversion method and biomethane using anaerobic digestion (Bhattacharya and Kumar 2010; Nong et al. 2020). Different biofuels produced from various aquatic weeds are mentioned in Table 2.2.

Table 2.2 Different types of bioethanol extracted from aquatic weed species

Aquatic weed specie	Biofuel produced	Yield	Reference
Pistia stratiotes (water cabbage)	Bioethanol	15.385 g/L	Whangchai et al. (2021)
Pistia stratiotes (water cabbage)	Biomethane	72.5%	Güngören Madenoğlu et al. (2019)
Eichhornia crassipes (water hyacinth)	Bioethanol	0.23 g/g	Figueroa-Torres et al. (2020)
Eichhornia crassipes (water hyacinth)	Biomethane	53–58%	Rathod et al. (2018)
Eichhornia crassipes (water hyacinth)	Biohydrogen	65 mmol/L	Carreño Sayago and Rodríguez (2018)
Victoria amazonica (giant water lily)	Bioethanol	4.82 g/L	Junluthin et al. (2021)
Pichia stipites (kariba weed)	Bioethanol	13.7 g/L	Chupaza et al. (2021)
Wolffia globosa (Asian water meal)	Bioethanol	170 g/kg	Soda et al. (2015)
Ceratophyllum demersum L. (coontail)	Bioethanol	2.92 g/L	Kusolsongtawee et al. (2018)
Lemna gibba L. (duckweed)	Bioethanol	20%	Dhruba et al. (2010)

2.4.1.3 Microalgae

Biofuel derived from algae has become a promising alternative fuel which ensures sustainable and stable transport fuel supply. Moreover, the use of algal diesel blend in gas turbine systems, compression ignition engines as well as aviation fuel has proven to be viable (Chiong et al. 2018). The required setup for harvesting, pretreatment and production questions the feasibility of microalgal biofuel generation. The extractives having nutraceuticals, therapeutics and cosmetic value derived from algal biomass, before as well as after oil extraction, have been reported in various studies. It has been reported that β-carotene, an algal chemical in its cis form, can create a profit of about USD600 million/kg. Additionally, leading market analyst companies have estimated that the value of omega fatty acids will stand at USD18.95 billion by 2020, carotenoid at USD1.53 billion by 2021, astaxanthin at USD814.1 million by 2022 and lutein at USD357.7 million by 2024 (Kumar and Bharadvaja 2020). *Botryococcus*, *Chlorella* sp., *C. reinhardtii*, *Dunaliella*, *Isochrysis galbana*, *Monodus subterraneus*, *Nannochloropsis*, *Phaeodactylum tricornutum*, *Scenedesmus*, *Spirulina* and *Tetraselmis* are biodiesel-rich microalgae genera with higher biomass productivity of about 20–200 mg/L/day. A study conducted using *S. dimorphus* and *S. obliquus* used chelate promoter, Ni(ii)-Schiff base and Ni/H_2 catalyst, to carry out higher yield of algal oil. The microalgal biodiesels were found to have higher cetane number and oxidation stability (Vadivel et al. 2020). It was found that through solvent extraction method, maximum ester yield of 82.33% was derived from *Botryococcus braunii* at 55 °C. It was also noted that the rate of conversion increases with increasing temperature (Prasad et al. 2015). Through Soxhlet extraction method, it was observed that in *Spirogyra* the lipid yield (55–80%) was higher in 100% dried sample and lowest in 50% dried sample (Konga et al. 2017), while *Cladophora* in similar growth conditions showed higher yield (90–95%) (Verma et al. 2016). Moreover, the concept of genome editing has revolutionized the biotechnological sector with its unique ability to identify, manipulate as well as isolate nucleic acid sequences changing the landscape of microorganism and crop-based biofuels (Shokravi et al. 2021). Few of the recent advancement in genome editing are described in Table 2.3.

2.4.2 Biofuel Production Using Non-edible Oilseeds

Urban expansion and agriculture have led to increase in deforestation leading to the decline in biodiversity and destruction of ecosystem. The competition towards the same resource in food and biofuel sector raises the debate over food versus fuel. Due to food scarcity in developing countries, conversion of food crop to biofuel could create a food shortage problem. Non-edible oil-based biodiesel production provides fuel security without compromising food supply (Islam et al. 2018). Furthermore, it can be grown in unproductive and waste land assisting in land reclamation (Francis

Table 2.3 Recent account of genome editing in microorganisms

Species	Technique used	Targeted gene	Impact	Reference
Chlamydomonas reinhardtii	CRISPR-Cas9	APT	Enhanced editing efficiency	Guzmán-Zapata et al. (2019)
Chlorella vulgaris UTEX395	CRISPR/Cas9	NR, APT	Enhanced editing efficiency	Kim et al. (2021)
Tetraselmis sp.	CRISPR-Cas9 RNP	AGP	Enhanced lipid production	Chang et al. (2020)
Chlamydomonas reinhardtii	CRISPRi	PEPC1	Enhanced biomass concentration and lipid accumulation rate	Kao and Ng (2017)

et al. 2005). Non-edible oil crops such as *Jatropha curcas*, *Pongamia pinnata*, *Calophyllum inophyllum*, *Madhuca indica*, *Ricinus communis*, *Hevea brasiliensis* and *Azadirachta indica* have proven to be promising alternatives as a biodiesel feedstocks (Azam et al. 2005). *Carica papaya* is a tropical fruit that weighs from 200 g to 3000 g. The seed content is 15–20% of wet weight of papaya fruit that is generally discarded (Daryono 2017). The oil content of these seeds is 30–34% with properties very similar to that of olive oil. Wong and Othman (2014), through enzymatic transesterification, extracted biodiesel from papaya seed using lipase at a molar ratio of 6:1 of methanol/oil. Daryono (2017) produced biodiesel from papaya seed using alkaline catalyst, and sodium hydroxide for the process of transesterification. The papaya seed oil can also be transesterified using KOH as a catalyst through single-stage method with 10:1 molar ratio of methanol/oil (Anwar et al. 2018). It has been observed that the physicochemical properties of biodiesel derived from papaya seed oil are very similar to that of diesel (Anwar et al. 2019). The typical yield of seed pods annually for *Ceiba pentandra*, a drought-resistant plant habitable in both subhumid and humid tropical regions, is estimated to be in the range of 300–1000 (Kachrimanidou et al. 2016). These pods contain cotton-like lustrous fibre embedded with about 120–175 seeds with the oil yield of 28% w/w. Under suitable conditions, the yield of seeds from *Ceiba pentandra* may be 30 kg annually. The pods are typically 10–25-cm-long ellipsoidal capsule with a diameter of 3–6 cm. According to Anwar et al. (2014), the iodine number for *Ceiba pentandra* seed lies at 80–100 which indicates nondrying on exposure to air and also has high free fatty acid content. The presence of cyclopropenoid fatty acids such as sterculic and malvalic acids causes physiological reaction in animals which makes *C. pentandra* a non-edible feedstock (Arumugam et al. 2020). *Citrus aurantium* is a fruit grown in Iran that has a lot of seeds that are regarded as waste. The oil content in seeds is about 38%. The maximum yield obtained from the novel feedstock via transesterification process at the temperature of 60 °C with catalyst concentration of 1 wt% was 97%, consistent with the ASTM standards (Almasi et al. 2021). Different non-edible oilseed and their oil content are mentioned in Table 2.4.

Table 2.4 Oil content in non-edible seeds

Species	Oil content (%)	Reference
Ricinus communis (castor)	49.2	Román-Figueroa et al. (2020)
Azadirachta indica (neem)	30–60	Karmakar et al. (2012)
Pongamia pinnata (karanja)	40	Calica (2017)
Moringa oleifera (drumstick)	30–40	Mohammed et al. (2003)
Hevea brasiliensis (rubber)	40–50	Ramadhas et al. (2005)
Jatropha curcas (jatropha)	40	Abdelrahman et al. (2020)
Sapindus mukorossi (soapnut)	51	Uzoh et al. (2014)

2.4.3 Biofuel Production Using Waste Products

Globally, every year millions of tonnes of waste are generated from household, industrial activities and agriculture that can create critical environmental and health issue if not disposed or managed properly. Through processes like gasification, pyrolysis, combustion and biological treatments, waste products/biomass may be converted to useful forms (Bhatt et al. 2018). Lignocellulosic waste as a feedstock has become popular for biofuel production (Kumari and Singh 2018). In recent years, focus on sustainability assessment of biofuel production has become vital as the emphasis on food versus fuel debate and the need for reduction in greenhouse gas emission has increased. Keeping these issues in mind, industrial waste residue, lignocellulosic waste and municipal solid waste are deemed as promising potential feedstocks (Cortez et al. 2018).

2.4.3.1 Municipal Solid Waste

Municipal solid waste (MSW) is commonly referred to as trash or garbage, discarded after use. MSW includes myriad of materials such as plastics, metals, medical wastes and hazardous materials. They generally have higher sulphur. This makes the selection of operating conditions and appropriate process paramount (Mukherjee et al. 2020). MSW can be categorized as recyclable consisting of non-lignocellulosic (glass, plastic, rubber, metals and others) and non-recyclable consisting of lignocellulosic (paper, wood waste, textile waste, yard waste, food/kitchen waste) components. In the lignocellulosic component, the main constituents are cellulose (15.30–65.80%), lignin (11.40–43.80%) and lastly hemicelluloses (7.20–16.50%) (Abdulyekeen et al. 2021). The average specific heat of combustion of MSW is 5–10 MJ/kg, while the elemental analysis depicts H_2, O_2, C, H_2O and ash to be 1.5–3.4, 8–23, 17–30, 24–34 and 18–43% (Fabry et al. 2013). There are 765 MSW-based waste to energy (WTS) plants globally. They are relatively scarce due to lack of support from the government and high capital cost (Wilson and Velis 2015). It is estimated that that per tonne MSW, the yield achieved can be 5.7 kg acetone, 12.2 kg butanol, 1.5 kg ethanol and 0.9 kg hydrogen (Meng et al. 2019). The fraction of MSW composed of kitchen waste, food waste and remnants from

Table 2.5 Bioenergy potential in various MSW

Component	Fixed carbon (%)	Moisture content (%)	Ash content (%)	Calorific value (MJ kg^{-1})	References
Kitchen food waste	7.19–16.60	9.60–79.00	0.80–20.93	15.34–18.10	Liu et al. (2014), Samad et al. (2018), and Huang et al. (2019)
Wood waste	17.29–20.16	5.21–66.00	5.29–7.31	17.73–19.46	Zhou et al. (2014), Samad et al. (2017), and Rago et al. (2020)
Paper	9.60–12.11	4.43–13.15	0.23–12.20	14.00–18.24	Zhou et al. (2014) and Rago et al. (2020)
Plastic	0.56	0.02–1.1	0.04–0.50	21.90–46.69	Zhao et al. (2016) and Rago et al. (2018)
Textile	0.71–13.75	5.25–13.75	0.41–3.56	16.51–20.16	Zhao et al. (2016) and Rago et al. (2020)

restaurants, residents, cafeterias, factory lunch rooms and gardens are called the organic fractions of municipal solid waste (OFMSW) (Campuzano and González-Martínez 2016). Since the availability of OFMSW is high and free of cost, its use in energy production could be an economical and technically viable alternative (Romero-Cedillo et al. 2017; Tyagi et al. 2018). It was observed that in source-segregated OFMSW, the biogas yield per tonne was slightly higher (111.1 m^3/tonne) in comparison with mechanically sorted OFMSW (105.3 m^3/tonne) (Seruga et al. 2020). Various component of municipal solid wastes and their bioenergy potential are mentioned in Table 2.5.

2.4.3.2 Waste Oils

Cooking and waste lubricating oil, degraded or contaminated after use, is generally referred to as waste oils. Waste oils derived from transmission oil, engine oil, cutting oil and hydraulic constitutes waste lubricating oil. Waste cooking oil is derived from coconut, soya bean, palm tree, sunflower, rapeseed, olive and cotton seed. Due to the presence of undesired substances and degraded additives, they are known to be hazardous substances which could bring about negative impacts to human health (e.g. reproductive, mutagenic and carcinogenic effects) and environment (e.g. fragile ecosystem, soil and water pollution and climate changes) (Lam et al. 2015). The open frying process alters the structure of cooking oil by free radical mechanism resulted by oxidation reaction. Through this primary oxidation process, hyperperoxide is produced which may oxidize further into 4-hydroxy-2-alkenals, a very reactive and toxic compound (Choe and Min 2007). Approximately, 50% of lubricating oil is produced as waste after operations resulted due to inefficiency of machinery. This has led to the generation of 20 million tonnes of waste oil.

There are new developments in waste oil-derived biofuel. Mićić et al. (2019) suggested a novel drying method which used silica as an absorbent instead of using carrier gas or distillation for water removal. It was noted that at 220 °C highest conversion can be obtained and FFA was reduced from the initial 8.6–1.6% at optimal conditions. Lam et al. (2019) mixed empty fruit batch from palm oil industry with waste oil for the production of high-quality solid fuel product with a higher heating value of 28 MJ/kg. Altalhi et al. (2021) performed catalytic pyrolysis of WCO through synthesis of heterogeneous acidic catalyst derived by sulphonation of modified alumina. Through the engine test investigation, the blend of biofuel-diesel indicated the suitability of B30 blend. Jahromi et al. (2021) studied the reaction between WCO and cyclic oxygenated hydrocarbons for novel biolubricant production through the process of hydrolysis, ketonization and Friedel-Crafts alkylation followed by hydrotreatment.

2.4.3.3 Sewage Wastes

The quantity of sewage sludge has increased with rapid growth in population globally. High content of organic matter, nutrient, salt, microelements, pathogens and heavy metals poses serious threat to health and well-being of human and ecosystem making its appropriate disposal mandatory (Kijo-Kleczkowska et al. 2016). Sewage sludge accounts for 1–2% of wastewater treated generated by wastewater treatment plants (Wzorek 2021). The relationship between generation of sewage sludge and the efficiency of treatment systems is proportional; the greater the sophistication of treatment plant, the higher waste generation occurs (Wzorek 2021). It has been estimated that the total electrical energy output utilized by these facilities is about 1–3% of a country (Capodaglio and Olsson 2020). In comparison with industrial sewage sludge, municipal sewage sludge contains higher amount of organic matter; this makes the municipal sewage sludge more suitable in regard to energy generation (Djandja et al. 2020). Wood processing and industrial pulping results in cellulose and lignin content in sewage sludge. Cellulose content ranges from 8.0 to 15.0, 8.0 to 15.0 and 7.0 to 9.7 wt% in untreated, digested and secondary sludge, respectively (Kacprzak et al. 2017). For higher heating value, lignin and volatile content in sewage sludge generally accounts for 11–26 MJ/kg, 23–29% and 30–88 wt%, respectively (Kacprzak et al. 2017).

Thermal processes including gasification, combustion and pyrolysis are applied for reducing both volume and mass of sewage sludge (Oladejo et al. 2019). Gasification and pyrolysis along with mass reduction can also generate gaseous and liquid fuel (Capodaglio et al. 2016). The pyrolysis product of sewage sludge includes CO_2, CO, H_2, CH_4, condensable compounds, hydrocarbons, bio-oil and biochar (Gao et al. 2016). It was observed that fast pyrolysis of sewage sludge at the temperature of 450–550 °C in fluidized bed reactors provides the oil yield of 30–70 wt% (Arazo et al. 2017), while for conventional pyrolysis, the yield of bio-oil extracted was around 51–80 wt% (Alvarez et al. 2015). Through fast pyrolysis, it was observed that depending on the material weight input, the yield of oil, gas and char was between 60 and 70 wt%, 10 and 20% and 15 and 25%, respectively (Djandja et al. 2020). For the production of solid biofuel, hydrothermal carbonization on sewage sludge was performed at different temperature and residence time. It was observed that hydrochar with highest HHV was produced at 150 °C for 30 min, while the maximum yield of hydrochar was found at 150 °C for 60 min (Silva et al. 2020). Wang et al. (2020) studied hydrothermal carbonization of sewage sludge mixed with phenolic wastewater and found that the hydrochar yield and higher HHV increased substantially by 1.83–31.11% and 1.01–10.01%, respectively, while ash content decreased by 1.39–25.68% (Wang et al. 2020). Ghodke et al. (2021) carried out pyrolysis of sewage sludge and obtained maximum yield of bio-oil, gas and biochar (22.4%, 18.9% and 58.7%, respectively) at 500 °C.

2.5 Challenges of Using Novel Feedstocks

There is an immense need for novel feedstocks for overcoming the demand for viable, feasible as well as sustainable biofuels. The biggest challenge of using novel feedstock is lack of available literature regarding the same. In regard to non-edible forest products, the main challenges are collection, harvest, seasonal availability and improper marketing channels (Shaah et al. 2021). Aquatic weeds have relatively lower lipid content in comparison with other biodiesel feedstock which results in lower biodiesel yield. High water content (≈90%) in tissue of aquatic weed may affect biofuel conversion process. The high content of sulphur in water hyacinth may result in production of corrosive substance that can reduce fuel efficiency (Nawaj Alam et al. 2021). Moreover, irregular supply, complex structural makeup and high pretreatment cost of aquatic weed pose a challenge (Alam et al. 2021). The high cost of production of biofuels from microalgae at industrial scale and concerns regarding the impacts of genetically engineered microalgae on environment are major challenges (Guldhe et al. 2017; Varela Villarreal et al. 2020). While the biowaste biorefinery has gained attention for its utilization of biowaste and converting it into high-value bioproducts, the basic problem is high pretreatment cost. With conventional approach, significant amount of chemicals is used generating large volume of hazardous sludge that requires safe disposal. There is a need for further research to look for alternatives and technology to overcome these issues.

2.6 Future Prospects and Conclusion

Biofuels as a renewable energy source have notable advantages. In comparison with fossil fuel, they significantly reduce carbon emission, particulate matter and micropollutants. They can be available on demand, are transportable and are easily storable energy source. For biofuel and bioenergy production, copious volume of feedstock is required. This has resulted in the development of novel feedstocks and novel techniques for existing feedstocks. To overcome the debate of food versus fuel, the potential of unconventional feedstocks such as non-edible oilseeds and forest products, aquatic weed, macro-/microalgae as well as waste products (waste oil, municipal solid waste and sewage waste) is being investigated. Though these novel feedstocks prove to be a promising source, there lays certain challenges in their implementation like irregular supply, high harvesting and pretreatment cost and improper marketing channel. Moreover, the genetic manipulation of feedstock causes a debate of its safety towards the environment. The future of these biofuels is based on developing cost-effective approaches for the most operationally efficient technologies and development of policies encouraging sustainable energy production through the recognition of various environmental benefits. Moreover, the study into circular economy as well as life cycle assessment is imperative to analyse the pros and cons of these novel feedstocks for biofuels.

References

Abdelrahman MAA, Yassin AAA, Hussein IH et al (2020) Production of biodiesel from *Jatropha curcas* seed oil. Gezira J Eng Appl Sci 12:59–67

Abdullah B, Muhammad SAFS, Shokravi Z et al (2019) Fourth generation biofuel: a review on risks and mitigation strategies. Renew Sust Energ Rev 107:37–50

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

Alam SN, Khalid Z, Guldhe A et al (2021) Harvesting and pretreatment techniques of aquatic macrophytes and macroalgae for production of biofuels. Environ Sustain 4:299–316. https://doi.org/10.1007/s42398-021-00178-6

Almasi S, Najafi G, Ghobadian B, Ebadi MT (2021) Waste to fuel: biodiesel production from bitter orange (*Citrus aurantium*) seed as a novel bio-based energy resource. Biomass Convers Biorefinery. https://doi.org/10.1007/s13399-021-01635-2

Altalhi AA, Morsy SM, Abou Kana MTH et al (2021) Pyrolytic conversion of waste edible oil into biofuel using sulphonated modified alumina. Alex Eng J 10:100075

Alvarez J, Amutio M, Lopez G et al (2015) Fast co-pyrolysis of sewage sludge and lignocellulosic biomass in a conical spouted bed reactor. Fuel 159:810–818

Anwar F, Rashid U, Shahid SA, Nadeem M (2014) Physicochemical and antioxidant characteristics of kapok (*Ceiba pentandra* Gaertn.) seed oil. J Am Oil Chem Soc 91:1047–1054. https://doi.org/10.1007/s11746-014-2445-y

Anwar M, Rasul MG, Ashwath N (2018) Production optimization and quality assessment of papaya (*Carica papaya*) biodiesel with response surface methodology. Energy Convers Manag 156:103–112

Anwar M, Rasul MG, Ashwath N, Nabi MDN (2019) The potential of utilising papaya seed oil and stone fruit kernel oil as non-edible feedstock for biodiesel production in Australia—a review. Energy Rep 5:280–297

Arazo RO, Genuino DAD, de Luna MDG, Capareda SC (2017) Bio-oil production from dry sewage sludge by fast pyrolysis in an electrically-heated fluidized bed reactor. Sustain Environ Res 27:7–14

Arumugam A, Yogalaksha P, Furhanashereen M, Ponnusami V (2020) Statistical optimization and enhanced synthesis of polyhydroxyalkanoates from *Ceiba pentandra* oil as novel non-edible feedstock. Biomass Convers Biorefinery 12:1–10

Azam MM, Waris A, Nahar NM (2005) Prospects and potential of fatty acid methyl esters of some non-traditional seed oils for use as biodiesel in India. Biomass Bioenergy 29:293–302

Beckmann J, Lehr F, Finazzi G et al (2009) Improvement of light to biomass conversion by de-regulation of light-harvesting protein translation in *Chlamydomonas reinhardtii*. J Biotechnol 142:70–77. https://doi.org/10.1016/j.jbiotec.2009.02.015

Bharti R, Guldhe A, Kumar D, Singh B (2020) Solar irradiation assisted synthesis of biodiesel from waste cooking oil using calcium oxide derived from chicken eggshell. Fuel 273:117778

Bhatt AK, Bhatia RK, Thakur S et al (2018) Fuel from waste: a review on scientific solution for waste management and environment conservation. In: Prospects of alternative transportation fuels. Springer Singapore, Singapore, pp 205–233

Bhattacharya A, Kumar P (2010) Transgenics for biofuel crops, vol 2. Springer, Berlin, pp 249–267. https://doi.org/10.1007/978-3-642-04812-8_6

Bioenergy IEA (2010) Bioenergy, land use change and climate change mitigation. Report for Policy Advisor and Policy Makers. IEA Bioenergy: ExCo 3

Calica PN (2017) Nodulation and nitrogen fixation of *Pongamia pinnata*. J Trop Crop Sci 4:1

Campuzano R, González-Martínez S (2016) Characteristics of the organic fraction of municipal solid waste and methane production: a review. Waste Manag 54:3–12

Capodaglio AG, Olsson G (2020) Energy issues in sustainable urban wastewater management: use, demand reduction and recovery in the urban water cycle. Sustainability 12:266

Capodaglio AG, Callegari A, Lopez MV (2016) European framework for the diffusion of biogas uses: emerging technologies, acceptance, incentive strategies, and institutional-regulatory support. Sustainability 8:298

Carreño Sayago UF, Rodríguez CD (2018) Construction of a biohydrogen and bioethanol production system from the biomass of the Eichhornia Crassipes. Preprints 50:393. https://doi.org/10.20944/preprints201805.0393.v1

Chang KS, Kim J, Park H et al (2020) Enhanced lipid productivity in AGP knockout marine microalga *Tetraselmis* sp. using a DNA-free CRISPR-Cas9 RNP method. Bioresour Technol:303, 122932

Chen P-H, Liu H-L, Chen Y-J et al (2012) Enhancing CO 2 bio-mitigation by genetic engineering of cyanobacteria. Energy Environ Sci 5:8318–8327

Chiong MC, Chong CT, Ng J-H et al (2018) Liquid biofuels production and emissions performance in gas turbines: a review. Energy Convers Manag 173:640–658

Choe E, Min DB (2007) Chemistry of deep-fat frying oils. J Food Sci 72:R77–R86

Chukwuneke JL, Ewulonu MC, Chukwujike IC, Okolie PC (2019) Physico-chemical analysis of pyrolyzed bio-oil from swietenia macrophylla (mahogany) wood. Heliyon 5:e01790. https://doi.org/10.1016/j.heliyon.2019.e01790

Chupaza MH, Park Y-R, Kim SH et al (2021) Bioethanol production from *Azolla filiculoides* by *Saccharomyces cerevisiae*, *Pichia stipitis*, *Candida lusitaniae*, and *Kluyveromyces marxianus*. Appl Biochem Biotechnol 193:502–514. https://doi.org/10.1007/s12010-020-03437-0

Cortez DV, Reis C, Perez VH, De Castro HF (2018) The realm of lipases in biodiesel production. In: Sustainable biotechnology-enzymatic resources of renewable energy. Springer, Cham, pp 247–288

Costa JAV, De Morais MG (2011) The role of biochemical engineering in the production of biofuels from microalgae. Bioresour Technol 102:2–9

Daryono ED (2017) Rapid in situ transesterification of papaya seeds to biodiesel with the aid of co-solvent. Int J Renew Energy Res 7:379–385

Dhadse S, Alam SN, Mallikarjuna Rao M (2021) Development of nutrient rich biofertilizer by co-vermistabilization of aquatic weeds using herbal pharmaceutical wastewater along with sediment of lake. Bioresour Technol Rep 13:100633. https://doi.org/10.1016/j.biteb.2021.100633

Dhruba S, Bala S, Arunachalam A (2010) Bioethanol production from *Lemna gibba* L. Curr Sci 98: 1162–1163

Djandja OS, Wang Z-C, Wang F et al (2020) Pyrolysis of municipal sewage sludge for biofuel production: a review. Ind Eng Chem Res 59:16939–16956

EASAC (2012) He current status of biofuels in the European Union, their environmental impacts and future prospects. EASAC Policy Report 19

Fabry F, Rehmet C, Rohani V, Fulcheri L (2013) Waste gasification by thermal plasma: a review. Waste Biomass Valorization 4:421–439

Fatma S, Saleem A, Tabassum R (2021) Wheat straw hydrolysis by using co-cultures of *Trichoderma reesei* and *Monascus purpureus* toward enhanced biodegradation of the lignocellulosic biomass in bioethanol biorefinery. Biomass Convers Biorefinery 11:743–754. https://doi.org/10.1007/s13399-020-00652-x

Ferreira S, Duarte AP, Ribeiro MHL et al (2009) Response surface optimization of enzymatic hydrolysis of *Cistus ladanifer* and *Cytisus striatus* for bioethanol production. Biochem Eng J 45: 192–200

Figueroa-Torres LA, Lizardi-Jiménez MA, López-Ramírez N et al (2020) Saccharification of water hyacinth biomass by a combination of steam explosion with enzymatic technologies for bioethanol production. 3 Biotech 10:432. https://doi.org/10.1007/s13205-020-02426-8

Fisher MJ, Rao IM, Lascano CE et al (1995) Pasture soils as carbon sink. Nature 376:473

Francis G, Edinger R, Becker K (2005) A concept for simultaneous wasteland reclamation, fuel production, and socio-economic development in degraded areas in India: need, potential and perspectives of Jatropha plantations. In: Natural resources forum. Wiley Online Library, Hoboken, NJ, pp 12–24

Gao F, Li C, Yang Z-H et al (2016) Continuous microalgae cultivation in aquaculture wastewater by a membrane photobioreactor for biomass production and nutrients removal. Ecol Eng 92:55–61

Gerbens-Leenes PW (2017) Bioenergy water footprints, comparing first, second and third generation feedstocks for bioenergy supply in 2040. Eur Water 59:373–380

Ghodke PK, Sharma AK, Pandey JK et al (2021) Pyrolysis of sewage sludge for sustainable biofuels and value-added biochar production. J Environ Manag 298:113450

Goldemberg J, Teixeira Coelho S (2004) Renewable energy—traditional biomass vs. modern biomass. Energy Policy 32:711–714. https://doi.org/10.1016/S0301-4215(02)00340-3

Guldhe A, Kumari S, Ramanna L et al (2017) Prospects, recent advancements and challenges of different wastewater streams for microalgal cultivation. J Environ Manag 203:299–315

Güngören Madenoğlu T, Jalilnejad Falizi N, Kabay N et al (2019) Kinetic analysis of methane production from anaerobic digestion of water lettuce (*Pistia stratiotes* L.) with waste sludge. J Chem Technol Biotechnol 94:1893–1903

Guzmán-Zapata D, Sandoval-Vargas JM, Macedo-Osorio KS et al (2019) Efficient editing of the nuclear APT reporter gene in *Chlamydomonas reinhardtii* via expression of a CRISPR-Cas9 module. Int J Mol Sci 20:1247

Heo HS, Park HJ, Park Y-K et al (2010) Bio-oil production from fast pyrolysis of waste furniture sawdust in a fluidized bed. Bioresour Technol 101:S91–S96. https://doi.org/10.1016/j.biortech.2009.06.003

Ho K-C, Chen C-L, Hsiao P-X et al (2014) Biodiesel production from waste cooking oil by two-step catalytic conversion. Energy Procedia 61:1302–1305

Huang J, Qiao Y, Wei X et al (2019) Effect of torrefaction on steam gasification of starchy food waste. Fuel 253:1556–1564

IEA (2018) World energy outlook 2018. IEA, Paris

Illman AM, Scragg AH, Shales SW (2000) Increase in chlorella strains calorific values when grown in low nitrogen medium. Enzym Microb Technol 27:631–635

Islam A, Primandari SRP, Yaakob Z (2018) Non-edible vegetable oils as renewable resources for biodiesel production: South-East Asia perspective. In: Advances in biofuels and bioenergy. IntechOpen, London

Jahromi H, Adhikari S, Roy P et al (2021) Synthesis of novel biolubricants from waste cooking oil and cyclic oxygenates through an integrated catalytic process. ACS Sustain Chem Eng 9: 13424–13437

Junluthin P, Pimpimol T, Whangchai N (2021) Efficient conversion of night-blooming giant water lily into bioethanol and biogas. Maejo Int J Energy Environ Commun 3:38–44

Kachrimanidou V, Kopsahelis N, Vlysidis A et al (2016) Downstream separation of poly (hydroxyalkanoates) using crude enzyme consortia produced via solid state fermentation integrated in a biorefinery concept. Food Bioprod Process 100:323–334

Kacprzak M, Neczaj E, Fijałkowski K et al (2017) Sewage sludge disposal strategies for sustainable development. Environ Res 156:39–46

Kao P-H, Ng I-S (2017) CRISPRi mediated phosphoenolpyruvate carboxylase regulation to enhance the production of lipid in *Chlamydomonas reinhardtii*. Bioresour Technol 245:1527–1537. https://doi.org/10.1016/j.biortech.2017.04.111

Karmakar A, Karmakar S, Mukherjee S (2012) Biodiesel production from neem towards feedstock diversification: Indian perspective. Renew Sust Energ Rev 16:1050–1060

Kijo-Kleczkowska A, Środa K, Kosowska-Golachowska M et al (2016) Combustion of pelleted sewage sludge with reference to coal and biomass. Fuel 170:141–160

Kim J, Chang KS, Lee S, Jin E (2021) Establishment of a genome editing tool using CRISPR-Cas9 in *Chlorella vulgaris* UTEX395. Int J Mol Sci 22:480

Konga AK, Muchandi AS, Ponnaiah GP (2017) Soxhlet extraction of *Spirogyra* sp. algae: an alternative fuel. Biofuels 8:29–35

Kumar L, Bharadvaja N (2020) A review on microalgae biofuel and biorefinery: challenges and way forward. Energy sources, part a recover. Util Environ Eff:1–24

Kumar A, Ogita S, Yau Y-Y (2018) Biofuels: greenhouse gas mitigation and global warming: next generation biofuels and role of biotechnology. Springer, New Delhi

Kumari D, Singh R (2018) Pretreatment of lignocellulosic wastes for biofuel production: a critical review. Renew Sust Energ Rev 90:877–891. https://doi.org/10.1016/j.rser.2018.03.111

Kusolsongtawee T, Wuttilerts T, Chulalaksananukul S, Maneechot L (2018) Bioethanol production from *Ceratophyllum demersum* L. and carbon footprint evaluation. Appl Sci Eng Prog 11:103–108

Lam SS, Liew RK, Cheng CK, Chase HA (2015) Catalytic microwave pyrolysis of waste engine oil using metallic pyrolysis char. Appl Catal B Environ 176:601–617

Lam SS, Tsang YF, Yek PNY et al (2019) Co-processing of oil palm waste and waste oil via microwave co-torrefaction: a waste reduction approach for producing solid fuel product with improved properties. Process Saf Environ Prot 128:30–35

Lamichhane G, Acharya A, Poudel DK et al (2021) Recent advances in bioethanol production from lignocellulosic biomass. Int J Green Energy 18:731–744

Leong WH, Azella Zaine SN, Ho YC et al (2019) Impact of various microalgal-bacterial populations on municipal wastewater bioremediation and its energy feasibility for lipid-based biofuel production. J Environ Manag 249:109384. https://doi.org/10.1016/j.jenvman.2019.109384

Liew WH, Hassim MH, Ng DKS (2014) Review of evolution, technology and sustainability assessments of biofuel production. J Clean Prod 71:11–29. https://doi.org/10.1016/j.jclepro.2014.01.006

Lin B, Ahmed F, Du H et al (2018) Plant growth regulators promote lipid and carotenoid accumulation in *Chlorella vulgaris*. J Appl Phycol 30:1549–1561. https://doi.org/10.1007/s10811-017-1350-9

Liu H, Ma X, Li L et al (2014) The catalytic pyrolysis of food waste by microwave heating. Bioresour Technol 166:45–50

Meng F, Ibbett R, de Vrije T et al (2019) Process simulation and life cycle assessment of converting autoclaved municipal solid waste into butanol and ethanol as transport fuels. Waste Manag 89:177–189

Mićić R, Tomić M, Martinović F et al (2019) Reduction of free fatty acids in waste oil for biodiesel production by glycerolysis: investigation and optimization of process parameters. Green Process Synth 8:15–23

Mohammed AS, Lai OM, Muhammad SKS et al (2003) *Moringa oleifera*, potentially a new source of oleic acid-type oil for Malaysia. Invest Innov 3:137–140

Mukherjee C, Denney J, Mbonimpa EG et al (2020) A review on municipal solid waste-to-energy trends in the USA. Renew Sust Energ Rev 119:109512

Naik S, Goud VV, Rout PK et al (2010) Characterization of Canadian biomass for alternative renewable biofuel. Renew Energy 35:1624–1631. https://doi.org/10.1016/j.renene.2009.08.033

Nanda S, Mohanty P, Pant KK et al (2013) Characterization of North American lignocellulosic biomass and biochars in terms of their candidacy for alternate renewable fuels. Bioenergy Res 6: 663–677

Nawaj Alam S, Singh B, Guldhe A (2021) Aquatic weed as a biorefinery resource for biofuels and value-added products: challenges and recent advancements. Clean Eng Technol 4:100235. https://doi.org/10.1016/j.clet.2021.100235

Nong HTT, Whangchai K, Unpaprom Y et al (2020) Development of sustainable approaches for converting the agro-weeds *Ludwigia hyssopifolia* to biogas production. Biomass Convers Biorefinery:1–9

Oladejo J, Shi K, Luo X et al (2019) A review of sludge-to-energy recovery methods. Energies 12: 60

Pandey VC, Singh K, Singh JS et al (2012) Jatropha curcas: a potential biofuel plant for sustainable environmental development. Renew Sust Energ Rev 16:2870–2883

Paul PEV, Sangeetha V, Deepika RG (2019) Chapter 9—Emerging trends in the industrial production of chemical products by microorganisms. In: Buddolla V (ed) Recent developments in applied microbiology and biochemistry. Academic Press, Cambridge, pp 107–125

Prasad ASA, Saravanan AS, Periyasamy S, Sivakumar P (2015) Optimization of various parameters on *Botryococcus braunii* for biodiesel production using NANO CaO catalyst. J Chem Pharm Sci. www.jchps.com. issn:974:2115

Radakovits R, Jinkerson RE, Darzins A, Posewitz MC (2010) Genetic engineering of algae for enhanced biofuel production. Eukaryot Cell 9:486–501

Rago YP, Surroop D, Mohee R (2018) Torrefaction of textile waste for production of energy-dense biochar using mass loss as a synthetic indicator. J Environ Chem Eng 6:811–822

Rago YP, Collard F-X, Görgens JF et al (2020) Torrefaction of biomass and plastic from municipal solid waste streams and their blends: evaluation of interactive effects. Fuel 277:118089

Ramadhas AS, Jayaraj S, Muraleedharan C (2005) Biodiesel production from high FFA rubber seed oil. Fuel 84:335–340

Rathod VP, Bhale PV, Mehta RS et al (2018) Biogas production from water hyacinth in the batch type anaerobic digester. Mater Today Proc 5:23346–23350. https://doi.org/10.1016/j.matpr.2018.11.072

Ren S, Lei H, Wang L et al (2012) Biofuel production and kinetics analysis for microwave pyrolysis of Douglas fir sawdust pellet. J Anal Appl Pyrolysis 94:163–169. https://doi.org/10.1016/j.jaap.2011.12.004

Rengel R, Smith RT, Haslam RP et al (2018) Overexpression of acetyl-CoA synthetase (ACS) enhances the biosynthesis of neutral lipids and starch in the green microalga Chlamydomonas reinhardtii. Algal Res 31:183–193. https://doi.org/10.1016/j.algal.2018.02.009

Rizwan M, Mujtaba G, Lee K (2017) Effects of iron sources on the growth and lipid/carbohydrate production of marine microalga *Dunaliella tertiolecta*. Biotechnol Bioprocess Eng 22:68–75

Rodionova MV, Poudyal RS, Tiwari I et al (2017) Biofuel production: challenges and opportunities. Int J Hydrog Energy 42:8450–8461

Román-Figueroa C, Cea M, Paneque M, González ME (2020) Oil content and fatty acid composition in castor bean naturalized accessions under Mediterranean conditions in Chile. Agronomy 10:1145

Romero-Cedillo L, Poggi-Varaldo HM, Ponce-Noyola T et al (2017) A review of the potential of pretreated solids to improve gas biofuels production in the context of an OFMSW biorefinery. J Chem Technol Biotechnol 92:937–958

Samad NAFA, Jamin NA, Saleh S (2017) Torrefaction of municipal solid waste in Malaysia. Energy Procedia 138:313–318

Samad ATP, Putri DN, Perdani MS et al (2018) Design of portable biodiesel plant from waste cooking oil. Energy Procedia 153:263–268

Sarayloo E, Simsek S, Unlu YS et al (2018) Enhancement of the lipid productivity and fatty acid methyl ester profile of *Chlorella vulgaris* by two rounds of mutagenesis. Bioresour Technol 250:764–769. https://doi.org/10.1016/j.biortech.2017.11.105

Seruga P, Krzywonos M, Seruga A et al (2020) Anaerobic digestion performance: separate collected vs. mechanical segregated organic fractions of municipal solid waste as feedstock. Energies 13(3768)

Shaah MAH, Hossain MS, Allafi FAS et al (2021) A review on non-edible oil as a potential feedstock for biodiesel: physicochemical properties and production technologies. RSC Adv 11: 25018–25037

Shi AZ, Koh LP, Tan HTW (2009) The biofuel potential of municipal solid waste. GCB Bioenergy 1:317–320

Shikha K, Chauhan YR (2012) Biodiesel production from non edible-oils: a review. J Chem Pharm Res 4:4219–4230

Shokravi H, Shokravi Z, Heidarrezaei M et al (2021) Fourth generation biofuel from genetically modified algal biomass: challenges and future directions. Chemosphere 285:131535

Silva ALP, Prata JC, Walker TR et al (2020) Rethinking and optimising plastic waste management under COVID-19 pandemic: policy solutions based on redesign and reduction of single-use plastics and personal protective equipment. Sci Total Environ 742:140565

Soda S, Ohchi T, Piradee J et al (2015) Duckweed biomass as a renewable biorefinery feedstock: ethanol and succinate production from *Wolffia globosa*. Biomass Bioenergy 81:364–368. https://doi.org/10.1016/j.biombioe.2015.07.020

Tan KWM, Lee YK (2017) Expression of the heterologous *Dunaliella tertiolecta* fatty acyl-ACP thioesterase leads to increased lipid production in *Chlamydomonas reinhardtii*. J Biotechnol 247:60–67. https://doi.org/10.1016/j.jbiotec.2017.03.004

Tariq M, Ali S, Khalid N (2012) Activity of homogeneous and heterogeneous catalysts, spectroscopic and chromatographic characterization of biodiesel: a review. Renew Sust Energ Rev 16: 6303–6316

Trentacoste EM, Shrestha RP, Smith SR et al (2013) Metabolic engineering of lipid catabolism increases microalgal lipid accumulation without compromising growth. Proc Natl Acad Sci 110: 19748–19753

Tulashie SK, Akpari EEA, Appiah G et al (2021) Acid hydrolysis of sawdust waste into bioethanol. Biomass Convers Biorefinery. https://doi.org/10.1007/s13399-021-01725-1

Tyagi VK, Fdez-Güelfo LA, Zhou Y et al (2018) Anaerobic co-digestion of organic fraction of municipal solid waste (OFMSW): Progress and challenges. Renew Sust Energ Rev 93:380–399

Urban W (2013) Biomethane injection into natural gas networks. In: The biogas handbook. Elsevier, Amsterdam, pp 378–403

Uzoh CF, Onukwuli OD, Nwabanne JT (2014) Characterization, kinetics and statistical screening analysis of gmelina seed oil extraction process. Mater Renew Sustain Energy 3:1–12

Vadivel M, Arvindnarayan S, Kumar G et al (2020) Biodiesel potentiality of microalgae species: evaluation using various nitrogen sources. Waste Biomass Valorization 11:1671–1679

Varela Villarreal J, Burgués C, Rösch C (2020) Acceptability of genetically engineered algae biofuels in Europe: opinions of experts and stakeholders. Biotechnol Biofuels 13:1–21

Vasić K, Knez Ž, Leitgeb M (2021) Bioethanol production by enzymatic hydrolysis from different lignocellulosic sources. Molecules 26:753

Verma P, Sharma MP, Dwivedi G (2016) Impact of alcohol on biodiesel production and properties. Renew Sust Energ Rev 56:319–333

Vikramathithan J, Hwangbo K, Lim J-M et al (2020) Overexpression of *Chlamydomonas reinhardtii* LCIA (CrLCIA) gene increases growth of *Nannochloropsis salina* CCMP1776. Algal Res 46:101807. https://doi.org/10.1016/j.algal.2020.101807

Wang J, Shen J, Ye D et al (2020) Disinfection technology of hospital wastes and wastewater: suggestions for disinfection strategy during coronavirus disease 2019 (COVID-19) pandemic in China. Environ Pollut 262:114665

Whangchai K, Inta W, Unpaprom Y et al (2021) Comparative analysis of fresh and dry free-floating aquatic plant *Pistia stratiotes* via chemical pretreatment for second-generation (2G) bioethanol production. Bioresour Technol Rep 14:100651. https://doi.org/10.1016/j.biteb.2021.100651

Wilson DC, Velis CA (2015) Waste management–still a global challenge in the 21st century: an evidence-based call for action. Waste Manag Res 33:1049–1051

Wong CS, Othman R (2014) Biodiesel production by enzymatic transesterification of papaya seed oil and rambutan seed oil. Int J Eng Technol 6:2773–2777

Wzorek M (2021) Solar drying of granulated waste blends for dry biofuel production. Environ Sci Pollut Res 28:1–10

Xue J, Balamurugan S, Li D-W et al (2017) Glucose-6-phosphate dehydrogenase as a target for highly efficient fatty acid biosynthesis in microalgae by enhancing NADPH supply. Metab Eng 41:212–221

Zhao L, Giannis A, Lam W-Y et al (2016) Characterization of Singapore RDF resources and analysis of their heating value. Sustain Environ Res 26:51–54

Zhou H, Meng A, Long Y et al (2014) An overview of characteristics of municipal solid waste fuel in China: physical, chemical composition and heating value. Renew Sust Energ Rev 36:107–122

Zhu L, Nugroho YK, Shakeel SR et al (2017) Using microalgae to produce liquid transportation biodiesel: what is next? Renew Sust Energ Rev 78:391–400