Suhaib A. Bandh
Fayaz A. Malla *Editors*

# Biofuels in Circular Economy

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*Dedicated*
*To*
*Prof. Azra N. Kamili*
*&*
*Dr. Navindu Gupta*

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*If every project has its secret inspiration or at least its one motivation, here that is the PEACE of my life.*

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Suhaib A. Bandh
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# Biofuels: Potential Alternatives to Fossil Fuels

**Fayaz A. Malla, Suhaib A. Bandh, Shahid A. Wani, Anh Tuan Hoang, and Nazir Ahmad Sofi**

## 1 Introduction

Primary oil consumption has skyrocketed in recent decades as the global human population has risen continuously for the past half a century. It has been over 40 years since the world's main energy consumption grew at its fastest pace since 1975. (Alam et al., 2012; Jones & Mayfield, 2012). Therefore, today's world faces two adverse challenges: energy shortage and environmental pollution (Gupta & Tuohy, 2013).

In recent decades, the energy crisis has risen as unsustainable sources like fossil fuels have been considerably reduced. Carbon dioxide ($CO_2$) emissions from fossil fuel use have risen sharply in recent years, and urgent action is needed to reduce these emissions to avoid the detrimental impacts of global warming. The high

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energy demand, coupled with environmental issues, has increased national security considerations around the globe (Gupta & Tuohy, 2013).

Non-edible and edible oils, as well as lignocellulosic biomass, can be utilized to produce organic fuels from renewable resources (e.g. wood). Biofuel production reduces reliance on fossil fuel oils and reduces uncertainties caused by the volatility in their prices. The increasing price has put more significant pressure on customers, companies, and investors because they compete against countries that use biofuels or renewable energy. On the other hand, biofuels are a source of renewable energy that can guarantee the country's economy while preserving the natural climate.

## *1.1 Unsustainable Energy*

The International Energy Agency estimates that the existing unsustainable paths of fossil fuel demand, trade fluxes, and greenhouse gas emissions will be pursued by 2030 because of a lack of public policy and efforts to regulate the situation. About 80% of the energy used consists of three fossil fuel types, including oil, coal, and gas. Fossil fuel combustion accounts for about 98% of $CO_2$ emissions (Hosseini et al., 2013). About 78.4% of the world's total energy sources were fossil fuels such as petroleum, natural gas, and coal.

## *1.2 Renewable Energy Sources*

Renewable energy accounts for 19% of global consumption, 10% of contemporary renewable energy and 9% of conventional biomass. Hydropower accounts for 3.8%, biofuels for 0.8%, and other renewable energy sources for 5.4% of today's renewable energy supply. In the fight against global warming and other environmental problems, the use of renewable energy sources is critical, both on the national and international levels. It produces cleaner energy and lowers greenhouse gas emissions in the atmosphere (Committee, 2014). Some renewable energy sources, including solar energy, wind, bioenergy, geothermal energy, hydroelectricity, and ocean energy, have a lower environmental impact than fossil fuels. (Singh & Olsen, 2011).

Palm oil is the world's largest edible oil source and is being promoted in Southeast Asian countries to produce biodiesel (Mukherjee & Sovacool, 2014; Shunmugam, 2009). Biodiesel is used as a pure or blended replacement for diesel, and because of its environmental friendliness, it is considered an attractive alternative fuel with a functionality that is the same as diesel (Jones & Mayfield, 2012). Microalgal biomass may also be turned into diverse biofuels utilizing different techniques such as liquefaction, pyrolysis, gasification, transesterification, fermentation, and digesting. In future, biofuel production by trans-esterifying microalgal oil and alcohol by hydrolyses and fermentation from microalgal carbohydrates will become more relevant (Chin et al., 2013).

## 2 Promise of Biofuels for Replacing Fossil Fuels

Many nations have made significant efforts to lessen their reliance on fossil fuels and enhance the efficiency of energy conversion (Demirbas, 2011). Currently, 88% of the world's energy needs are met by burning fossil fuels like gasoline, coal, and natural gas (Adenle et al., 2013). Fossil fuels are non-renewable and will run out in the future if we continue to use them. As a result, better measures are required to safeguard energy resources and reduce $CO_2$ emissions (Fernandes et al., 2007).

There has been significant global growth in liquid biofuels (Fernandes et al., 2007). First-generation biofuels have reached commercial standards and are already developed in the USA, Brazil, and the European Union with food and oil crops, including sugarcane, sugar beet, herbal oils, and animal fats as their key sources (Demirbas, 2011; Fernandes et al., 2007). Agricultural wastes, forest harvesting residues, and wood processing residues, as well as non-edible components from food crops such as jatropha, mahua, tobacco seed, and miscanthus, are the primary biomass sources for second-generation biofuels (Alam et al., 2012). As a result, they are less harmful to the environment and less competitive with arable land than first-generation biofuels. Because of this, the economic viability of second-generation biofuels is currently limited (Alam et al., 2012; Demirbas, 2011).

Known as third-generation biofuels, microalgae-derived biofuels have the potential for large-scale production. It appears that only microalgae can replace fossil fuels as a feedstock (Brennan & Owende, 2010; Chisti, 2007; Hossain & Davies, 2012; Karaj & Müller, 2014; Kaya et al., 2009; Khayoon et al., 2012; Li et al., 2013; Mata et al., 2010; Mihaela et al., 2013; Satyanarayana & Muraleedharan, 2011). Microalgae can grow swiftly and thrive in even the most hostile environments. The growth of microalgae can be enhanced by selecting the right species and the right habitat. Large open ponds or photo-bioreactors (PBR) are typically used to grow microalgae and collect other biofuels.

## 3 Biofuels as an Alternative to Fossil Fuels

Research shows some advantages and drawbacks of biofuel development with good and bad characteristics (Shunmugam, 2009). Biofuels have three significant advantages over conventional petroleum. First and foremost, we become less reliant on foreign oil. Second, it contributes to the growth of the rural economy by creating jobs. For a third reason: burning biofuel produces no or very little emissions, as the carbon dioxide created is recycled during the photosynthesis process by plants that produce oilseeds for biodiesel manufacture (Singh & Olsen, 2011).

On the other hand, it is less suitable in low temperatures and attracts moisture (Shunmugam, 2009). Technologically speaking, biofuels can compete with oil without significant modifications to the engine. Biofuels are also preferable due to their excellent lubrication qualities and lower exhaust emission profiles. However, poor oxidation stability, high density, and a lower calorific value than petroleum have limited their use directly in the CI engine. Most problems with biofuels can be minimized by adding sufficient additives or blending them with petroleum. Further, the earlier that raw material cost contributes primarily to biodiesel production. Therefore, suitable raw materials for biofuel production are very important (Mukherjee & Sovacool, 2014).

## 4 Energy Generation from Microalgal Biofuels

Microalgal biomass and biofuels can be used in power production. The ability of microalgal biofuels to replace internal combustion engine fossil fuels is high. In coal co-firing, microalgae can produce electricity to reduce greenhouse emissions and lower coal consumption.

### *4.1 Microalgal Biofuels for Internal Combustion Engine*

In the last few years, renewable feed biofuels for transportation have become a promising approach (Ziolkowska & Simon, 2014). Biofuels like bioethanol and biodiesel can replace two primary fossil fuels (gasoline and diesel) used in the transportation sector (Ziolkowska & Simon, 2014). Microalgal biofuels can eventually substitute biodiesel production with their chemical properties, which depend on the fatty acid profile of the microalgal biomass (Demirbas & Demirbas, 2010).

Microalgal fatty acids like methyl esters are based on their growth parameters, including environmental temperature, light strength, nutrition, and growth time (Borowitzka & Moheimani, 2013). High oleic acid (C18:1) content enhances ignition efficiency and combustion heat as well as cold filter plugging point and oxidation stability as well as the viscosity and lubricity of the fuel. Oleic acid in microalgal fatty acids provides great stability for long-term storage and lowers the cold filter clogging threshold in cold locations. As a result, microalgal species' increased fatty acid oleic acid concentration makes them ideal for biodiesel generation (Borowitzka & Moheimani, 2013; Johnson & Wen, 2009; Lee et al., 2010). *Chlorella* sp. Saccharomyces cerevisiae, *Picochlorum* sp., *Botryococcus* sp., Scenedesmus sp., and *Nannochlopsis oculata* contain a lot of oleic acids, which makes them ideal for biodiesel synthesis.

In comparison to fossil fuels, the combustion efficiency of oxygenated molecules like methanol, ethanol, and biodiesel has increased with the use of biofuels. Biodiesel or pure biodiesel has been found to improve the efficiency of internal combustion engines by combining it with fossil fuels (Demirbas & Demirbas, 2010).

### 4.2 Electricity Production from Microalgal Biomass

Vast quantities of electricity produced worldwide by coal-fired power stations have a significant environmental impact. The world's coal consumption is projected to rise by 56% between 2007 and 2035 (Islam et al., 2013). Biomass, considered an attractive renewable fuel, is a viable alternative to coal. Microalgae grown in open pond systems are among the most promising biomass feedstocks for co-firing (Kucukvar & Tatari, 2011). It is a cost-effective solution to power generation and a strategy to minimize greenhouse gas emissions from fossil fuels. It provides a broader variety of biomass supplies supporting the growth of fuel supply and infrastructure [29]. By using $CO_2$ from the power station, microalgae can reduce $CO_2$ emissions substantially from the atmosphere. This process could subsequently reduce greenhouse gas emissions. For the process to be more environmentally friendly, a balance must be struck between the generation of microalgae and microalgae co-firing (Kucukvar & Tatari, 2011).

## 5 Sustainability Analysis

When it comes to the conversion of biomass into biofuels, sustainability is a major problem. Biomass used in the manufacture of biofuels should come from a sustainable source and adhere to standards for sustainable biodiversity and land-use change that have been demonstrated time and time again (Arjona-Antolin et al., 2012; Kadam, 2002; Tillman, 2000; Zhu, 2010). Mathematical models such as LCA, material flow accounting, and strategic environmental assessment are used to investigate the sustainability aspects of biofuel production. Environmental, social, and economic aspects are all considered in sustainability research. The effects of air pollution on human health and the condition of the environment must be considered throughout the supply chain.

Similarly, research must be conducted to determine how we can sustainably use existing biomass resources. Recent developments in biofuel research have led to the production and use of models and computer resources at different operational levels. These include large crop models, simulations of chemical process design, LCA models, and mathematical optimization tools (Arjona-Antolin et al., 2012). All these studies provide new insights into biofuel sustainability. The first phase of research involves field and laboratory tests. These include researching biomass cultivation methods, optimizing process parameters for biofuels, understanding the kinetic reactions, etc. If these laboratory procedures are developed, the following research stage is to be carried out. It includes applying agricultural crop models and a typical study of process design. A variety of large-scale crop models have been developed to simulate bioenergy crop production, including herbaceous crops (e.g. EPIC, ALMANAC, MISCANMOD, MISCANFOR, WIMOVAC, Agro-IBIS, Agro-BGC, APSIM, AUSCANE, LPJmL, CANEGRO), woody bioenergy crops (e.g. 3PG, SECRETS), and crassulacean acid metabolism crops (e.g., EPI) (George et al., 2015). Biomass, nutrient cycle, water consumption, and carbon emission levels are all simulated using these models.

In the third level of analysis, goods, energy, and emissions are taken into account across the supply chain. Consideration of environmental consequences goes beyond typical process design parameters. The life-cycle assessment (LCA) is a popular tool for assessing a product or process's environmental impact throughout the course of its entire existence (Nair et al., 2012; Pourhashem et al., 2013). The environmental sustainability of biofuels has been studied using the LCA method. Environmental products and services will be available throughout the whole supply chain once the study has reached its final stage of ecosystem size. Concerns about land usage, especially its impact on greenhouse gas emissions and biodiversity, are at the heart of sustainable biomass development. Since no more land is being used, reusing agricultural and forestry waste and leftovers is an environmentally friendly option. Potentially applicable biomass studies have a few holes in them. Unused acreage for bioenergy crops and how natural grasslands contribute to this potential are two major sources of uncertainty. Future farm production and animal product consumption expectations have a considerable impact on outcomes. This uncertainty is compounded by the fact that the future demand for other uses, such as animal feed and soil quality enhancement, is quite unpredictable. Another source of uncertainty is the strict formulation and implementation of the conditions for sustainable biomass development.

Food and fuel crop rivalry for land is a major obstacle to the long-term viability of biofuel production. As the world's population grows, so does the need for food, water, and energy. Increasing demand for biofuels and limited agricultural land have led to a conflict between food and fuel, which might harm LUC and food security. Agriculturalists are more inclined to switch from food to fuel crops since the financial rewards are greater and the employment opportunities more secure. Food prices rise as a result of a decline in food supply (connected to food security) (Demırbas, 2017; Joshi et al., 2017; Luthra et al., 2015; Dang et al., 2014). Many agricultural commodities have had a long-term association with the development of biofuels, despite their apparent lack of connection to food costs (Obidzinski et al., 2012). Rising oil costs used for biofuels have had a long-term influence on agricultural product pricing. The substitution impact subsequently spreads to other agricultural products. According to the author, in the absence of biofuel production, changes in oil prices have a little long-term effect on agricultural commodities save for rapeseed prices (Obidzinski et al., 2012). Other studies have calculated the influence of biofuel production on the price of crops, as well. 19 research shows that for every billion gallons of corn ethanol produced, long-term maize prices rose by an average of 2–3% (Condon et al., 2013; Paris, 2018). In poor nations, increasing food costs can lead to malnutrition and famine as a result of biofuel production (Hertel et al., 2010; Raman et al., 2015).

Local environmental problems and energy instability would be exacerbated by incentives for the development and export of feedstock to affluent nations for the production of biofuels (Condon et al., 2013). The issues of long-term viability for trash, non-food crops, and algae-based biofuels in the second and third generations are less severe (Obidzinski et al., 2012). Increasing the cyclical economy and reducing social and environmental concerns are also possible outcomes of waste technology development.

## 6 Potential Economic Benefits of Biofuel Production

The use of biofuels instead of traditional fossil fuels has the potential to provide a number of benefits. Biofuels are created from renewable feedstocks, unlike fossil fuels, which are depleted over time. Because of this, their usage and development might continue indefinitely. Biofuels can cut the GHG emissions of conventional fuels, according to academic research based on current economic patterns (Hertel et al., 2010; Raman et al., 2015). Because their feedstock may be produced on marginal land, second and third-generation biofuels have a significant potential to reduce GHG emissions from conventional fuels.

There is no extra agricultural production required in the case of waste biomass; indirect market-mediated GHG emissions are insignificant if the trash does not have any other productive application. It is possible to create biofuels in the USA, reducing the reliance on imported fossil fuels (Hertel et al., 2010). We may be less exposed to the negative consequences of interrupting fossil fuel supplies if biofuel production and use decrease fossil fuel intake (Huang et al., 2013). We can also lower the price of oil by decreasing our usage, which in turn lowers the price of oil for everyone else (Hertel et al., 2010). Carbon dioxide ($CO_2$) may be captured and converted into biomass more quickly in third and fourth-generation biofuels made from microalgae and genetically engineered algae. In comparison to traditional biofuels, microalgal biofuels are less expensive and don't compete with food crops for resources. In addition, microalgae farming requires substantially less area and changes the usage of that land significantly less. All things considered, third- and fourth-generation biofuels are more cost-effective than first- or second-generation biofuels or fossil fuels.

## 7 Potential Economic Disbenefits and Impacts of Biofuel Production

Biofuel feedstocks include a number of crops that would otherwise be used for animal feed. More land usage, increased pollution, and higher food costs might all result from turning these crops into biofuels. Competition for food production resources might arise from the usage of cellulosic feedstock (land, water, fertilizer, etc.). Biofuel production, it has been found, might lead to a slew of unintended consequences. Due to the release of carbon dioxide from the ground, changes in land use will lead to a rise in global warming gases (GHGs) (US Environmental Protection Agency, 2010).

Soybean in the Amazon and oil palm in Southeast Asia are examples of biofuel feedstock that contributes to high GHG emissions from tropical forests (Searchinger et al., 2008). A rise in the price of cellulosic food can lead to the expansion of agriculture onto previously undeveloped territory, resulting in GHG emissions and biodiversity losses (Fargione, 2008). As a byproduct of biofuel production, greenhouse gases (GHGs) may be emitted. Biofuel production and consumption, including indirect land-use changes, may produce greater GHG emissions than fossil fuels depending on the time horizon of the research (Fargione et al., 2008; Melillo et al., 2009). Biofuel feedstock expansion, particularly for food crops like maize and soya, has also been demonstrated to increase water pollution from nutrients and pesticides, according to study findings (Mosnier et al., 2013). A wide variety of estimates in the literature implies that the usage of biofuels would lead to increased agricultural prices, although economic modelling shows otherwise.

# 8 Carbon Capture and Storage Potential of Biofuels

## *8.1 Environmental Footprint*

Biofuels may also be used as an additive for fossil fuels to lower carbon monoxide emissions and particulate matter. Second-generation biofuels can have a substantial influence on the environment depending on the route and feedstock they are made from, as well as other factors such as the climate and soil conditions in which they are grown. Second-generation biofuel production must thus be assessed and mitigated to ensure the long-term viability of the process by assessing and mitigating changes in the indirect usage of soil. For bioenergy facilities, precise mapping and land-use planning are necessary. Many first- and second-generation biofuels have run into serious sustainability and technical issues, making it difficult to properly produce biofuels and do GHG emission monitoring. For different biofuels, the US Environmental Protection Agency also implements some GHG emission figures for environmental and ecological impacts. The “ecological” or “environmental” footprints are regarded as indicators of energy use and waste absorption. Soil, carbon, water, and material footprints all play a role in environmental issues, as do social and economic aspects as well.

## *8.2 Carbon Footprint of Biofuels*

International Energy Agency estimated that the total carbon footprint (National Research Council, 2011) of biofuels is expected to rise from 0.085 billion (bn) gha in 2010 to 0.64 bn gha by 2050 (Hammond, 2015), with the increase in bioethanol and advanced biodiesel production is the leading cause of the same. Based on sugarcane, bioethanol generated 0.80 kg $CO_2$e/L of biofuels, whereas advanced biofuels produced 1.22 kg $CO_2$e/L. It is estimated that by 2050, sugarcane would account for 18% of the overall carbon footprint, and that figure is projected to remain the same. The carbon footprint of sugar beet and corn traditional bioethanol in 2010 was 0.051 billion gha (billion hectares worldwide) and was projected to grow to 0.059 billion gha by 2020 (Hammond, 2015). In 2020, advanced biofuels resulted in less than 50% of GHG relative to traditional first-generation biofuels (FGB). The IEA biofuel forecast assumed that the wastes and residues produce 50 per cent of the advanced biofuels and biomethane.

## 9 Techno-Economic Analysis of Fossil Fuels-Biofuels Transition

Biofuels and the bioeconomy continue to be driven by the need for long-term economic growth that does not rely primarily on fossil-based resources. Sustainable economic, social, and environmental outcomes can be achieved using biofuels. They ensure energy security by displacing fossil fuels, which are in short supply, with domestically produced fuels, which reduces reliance on high-cost imports. Biofuels have the potential to cut GHG emissions across the whole lifespan of conventional fuels significantly (International Energy Agency, 2011; Hertel et al., 2010). Rural and local economies benefit greatly from the development of biofuels. Biofuel development has the potential to create new employment, improve revenue, and supply local goods and services because of the widespread availability of biomass and the need to build new power stations to process it (Dang et al., 2014). As well as a reduction in local and national dependence on imports of conventional fuels, the economic benefits of biofuels include value-added feedstock and business potential for crops, new plant and machinery investment, new rural jobs and income options. Because second- and third-generation biofuels are less cost-competitive than first-generation biofuels (in terms of production and processing tools and technical facilities), current demand for biofuels is heavily dependent on government policies like mandatory quotas, despite these advantages (in terms of environmental sustainability).

Feedstock type, agricultural land and labour cost methods, processing technology, and plant size all have a role in determining the cost of producing biofuels. Due to the unpredictability of biomass resource availability, power plants are often constructed for small-scale operations concerning economies of scale. To add insult to injury, biofuels provide nothing in terms of energy density or biomass collecting and transportation expenses. The high domestic biomass availability, low per capita consumption, and low labour costs in OECD countries make biofuel production three times more expensive than in countries using conventional fuels (Luthra et al., 2015). This is in contrast to developed countries where the cost of biofuel production is comparable to that of conventional fuels (Moioli et al., 2018). To fulfil the target of reducing GHG emissions by 6% and expanding the biofuel sector, fuel blending and incentives have been adopted. The overall biofuel percentage for cars that can run on both gasoline and diesel is only 10% (COM, 2017, p. 284 final). Higher mixes and additional marketing alternatives necessitate new automotive standards, engine and vehicle adaptations, and new gasoline distribution infrastructures (Goldemberg et al., 2008). Biofuel production and distribution are also heavily influenced by changes in the price of conventional fuels (Gomiero, 2018). Since economic incentives and environmental responsibilities are so important to biofuel production, they will likely stay so. Overall, the demand for biofuels is expected to increase by 37% by 2040. (Pourhashem et al., 2013).

On the other side, biofuel development has uncovered contentious socio-environmental problems. Some scholars have reported that biofuels have limited GHG emission reduction and environmentally sustainable development in general (US Environmental Protection Agency, 2010; Searchinger et al., 2008). These arguments are based on the effects of deforestation, habitat loss, the use of fertilizers for fuel crops, and improvements in indirect land use. Other adverse environmental effects of biofuel production are water contamination from nutrients, chemicals and sediments or drainage from cultivated land and biofuel processing (Fargione et al., 2008). The primary socio-economic and environmental aspects that have been adversely affected (mainly first generation) by biofuels include (i) change in indirect land use (LUC), price of food crops, and food protection, and (ii) the lack of access to capital associated with rising land pressures.

## 10 Fossil Fuel-Biofuel Transition for Climate Change Mitigation

A lengthy controversy has emerged in the literature about whether biofuels help combat climate change. If indirect emissions such as land-use emissions are overlooked when agricultural land is expanded to produce biofuels, they certainly reduce greenhouse gas (GHG) emissions (Fargione et al., 2008; Dang et al., 2014). On the other hand, there is no consensus in the literature on the effects of biofuels on net GHG emissions when land-use changes are considered. Searchinger et al. argued that using current agricultural land for biofuel production is likely to emit as many GHG emissions as corn-based ethanol in 167 years through fossil fuel substitution in the USA, mainly via indirect land-use changes (Searchinger et al., 2008).

## 11 Performance and Emission Characteristics

Auto-ignition is a vital element of diesel, and it is characterized by a fuel cetane number or cetane index, which indicates how quickly the fuel will start to burn out if the cetane number or index is increased. US petroleum diesel has a cetane index in the 40 s, and European diesel has a cetane index in the 50 s, on average. It has been reported that cetane levels for biodiesel ranged from 45.8 to 56.9 for methyl esters of soybean oil and averaged at 50.9 for methyl esters of soybean oil. While cetane levels tend to be low in petroleum diesel, proper production management might provide high-end biodiesel products with cetane numbers. Using catalytic cracking and coking, American refiners boost the output of high-octane gasoline and low-cetane diesel from their refineries.

Additionally, diesel fuel's lubricating characteristics must be calculated. Lubrication fuel is required for various fuel injectors and fuel pumps. As the National Biodiesel Board points out, more than half of the diesel oil samples supplied in the USA did not meet the minimal lubricity standards required. Because of its superior lubricity, biodiesel is superior to today's low-sulphur petroleum diesel, which contains 500 parts per million of sulphur (ppm). In low-sulphur petroleum diesel, a 1–2% volumetric biodiesel blend greatly improves lubricity. Even said, different lubricant additives can have the same effect at lesser costs, so keep that in mind.

The performance of biodiesel is also compromised. Temperatures below freezing have a significant impact on biodiesel production. During cold weather, the wax crystals that develop in diesel fuel block the fuel lines and filters of a car. Temperatures at which gasoline samples become foggy and wax crystals begin to form are known as "cloud points." Diesel fuel forms a solid at low temperatures and cannot be pumped. The "pour point" is the temperature at which the gasoline will not change. In comparison to petroleum diesel, the cloud and pour points of biodiesel are greater. As a result, vehicles fuelled by biodiesel may experience greater driving issues in colder winter temperatures than vehicles fuelled by petroleum diesel. The biodiesel's solvent characteristic may cause other issues in the fuel system. Seals used in older automobiles and machinery fuel systems may not be compatible with biodiesel and must be changed when using biodiesel mixes. Cars and machines must be used with caution while using biodiesel for the first time. The presence of oxygen increases combustion by minimizing hydrocarbon, carbon monoxide, and particle emissions, which can be harmful to the health of the environment. Those who utilize biodiesel say that it has a cleaner burn and a more pleasant aroma than standard diesel engines. Di-tert-butyl peroxide at 1% or 2-Ethylhexyl nitrate at 0.5% can lower the aromatic content of petroleum diesel from 31.9 to 25.8% by adding cetane boosters to the biodiesel.

## 12 Conclusions

In 2010, global primary energy consumption grew by 5.6%, the most in 40 years. High carbon dioxide emissions are created by fossil fuel consumption for power and transportation ($CO_2$). Biofuel production decreases fossil fuel dependency and price volatility. Biofuel is a renewable energy source that protects the economy and climate. Increased fossil fuel prices have put pressure on customers, corporations, and investors that compete with nations that employ biofuels or renewable energy. Global $CO_2$ emissions are expected to quadruple by 2035, or 1.6% annually. High $CO_2$ levels prevent thermal infrared radiation from reaching space. $CO_2$ emissions from fossil fuel burning are 98%. Renewable energy is crucial to global and domestic energy and environmental challenges. Solar, wind, biofuel, geothermal, hydroelectricity, and ocean energy have a minimal environmental effect. Non-renewable fossil fuels dwindle. Therefore, a better approach to energy conservation and $CO_2$ reduction is needed. Biofuel offers several advantages over petroleum. It decreases our oil reliance. It boosts the rural economy. Because biodiesel facilities recycle carbon dioxide, it has zero or minimal emissions. Without engine adjustments, it can compete with oil. Biofuels provide better lubrication and reduced exhaust emissions. Adding enough chemicals or combining them with petroleum can solve most biofuel difficulties. Animal dung, industrial wastes, waste/water, and crops can be used to make biofuels.

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# Biofuel Economy, Development, and Food Security

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## 1 Introduction

The biofuel economy is seen to expand exponentially in the twenty-first century. Howarth et al. (2009) already reported the upsurge in the generation of biofuels as means to energize the economy in developing countries. Biofuel generation is recognized to encourage economic development through the opening of new prospects for enterprise development, creating employment, and increasing earnings among communities. Although the potentials of biofuels to promote economic growth are vast, their production may lead to a variety of environmental impacts as a consequence of the land-use change, changes in agricultural practices, massive transportation of the biomass for biofuel production, and the management of waste materials. The massive increase in biofuel production may disrupt the agri-food system, which can threaten food security and the biodiversity that supports pollination, soil nutrient cycling, among others. Biofuels would become more significant in future systems along with the fast-growing economy and rapid technological advancement (Balat & Balat, 2009; Barreto et al., 2003; Kraxner et al., 2013). These conditions can be foreseen. However, there may be some disruptions given the environmental challenges, such as climate change and when conventional energy sources compete with food sources.

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Understanding the diverse aspects of the agriculture landscape to meet the demands for food and biofuel that rely on agricultural biomass is essential to satisfy the needs of the exponentially growing global population. The increase in biofuel production over the last decade and the formulation of biofuel policies have altered the agricultural landscape worldwide, particularly related to land use and trade. At present, ethanol is produced mainly from sugarcane and corn, particularly from Brazil and the USA (Chum et al., 2014; Elshout et al., 2019; Pereira et al., 2019). Generally, biodiesel is generated from rapeseed (canola oil), soybean, and oil palms, which are also used for food. The competing demands for food and biofuels would impose major strains on global food provisions (OECD & FAO, 2007). The overall reduction in cropland results in reduced global greenhouse gas emissions (Dumortier et al., 2021). As a result, important long-term policy implications may occur due to changes in fuel efficiency requirements or ethanol blending limits that influence the economic and environmental impacts. Food-bioenergy integration is the way forward as it optimizes natural capital resources and considers wider environmental and socio-economic sustainability (De Menna et al., 2015; Guo et al., 2020; Kline et al., 2017). The integrative approach enables whole systems modelling to address the interconnection and interaction of resource-food-bioenergy systems while optimizing supply chains.

## 2 Current Scenario of Biofuel Economy in Asia

Brazil and the USA are known as the leaders in biofuel production, mainly from sugarcane and corn, respectively, that produced approximately 70% of the global biofuel supply. The global fuel price hike and the concerns over gas emissions prompted countries all over the globe to consider biofuels as an alternative. In Asia, the largest producers of biofuels are Indonesia, Malaysia, the Philippines, Thailand, China, and India. In Malaysia, the promotion of biodiesel results in a cleaner environment and energy security; however, it is hampered by the competing demands for food, feedstock prices, and fuel subsidies (Johari et al., 2015). Moreover, stakeholder engagement is vital to the development and adoption of Malaysian biodiesel, hence, the need for structural reforms to address the challenges. In the Philippines, green economy projects are promoted to encourage the production of agro-industrial commodities for climate change mitigation, environmental rehabilitation, and inclusive rural economic growth. Despite the national programmes, critical questions about the realization of the vision of the green economy in the Philippines have been raised. The questions are on the risks to upland environments and populations (Montefrio & Dressler, 2016). The Philippines implemented an ambitious programme of biofuel production to reduce dependency on imported fuel, create employment and jobs in rural areas, and curb greenhouse gas emissions. However, Stromberg et al. (2011) reported that yield loss in biofuel crops could be 98% in major production centres due to wind affecting the potential rural incomes. The indirect land-use change may also affect the greenhouse gas (GHG) emissions targets. The biofuels programme also created some tensions with stakeholders in the uplands, including the indigenous peoples. The contract farming of *Jatropha* on indigenous lands in the Philippines has disrupted the smallholder production systems of the indigenous groups since these are being phased out or transformed by the global biofuels network (Montefrio & Sonnenfeld, 2013). The Philippines is the first country in Southeast Asia to enact legislation on biofuels; thus, it is recognized as a model for its decisive mandates in this area. However, there are debates that point out the relative inability to influence the country's biofuels policy which can be attributed to perceptions among policymakers and the general public that forest conservation has no immediate socio-economic relevance and that, given their dismal state, primary forestlands across much of the archipelago lack significant environmental value (Montefrio & Sonnenfeld, 2011).

## 3 The Competing Global Demands for Food and Biofuel as the Population Builds up

Biofuel promotion in Asia targets higher economic benefits and reduced gas emissions, and rural development. Conversely, this affects food security, especially for feedstocks grown in agricultural lands (Langeveld et al., 2014; Panichelli & Gnansounou, 2015; Taheripour et al., 2017). The extensive expansion of biofuel production areas caused an indirect land-use change, disrupting forests, wetlands, or natural grasslands that likely increase emissions and damage biodiversity. In the case of palm oil as the main source of biodiesel, the main environmental sustainability considerations include the capacity to reduce GHG emissions, carbon balance, repercussions on forestry, biodiversity, and soil and water quality (Mukherjee & Sovacool, 2014). The palm oil biodiesel affecting food security in Southeast Asia has been recognized, along with the impact on rural livelihoods and land tenure.

Meeting the competing demands for food and energy without negatively impacting the environment through the conversion of land uses, disrupting the habitats of biodiversity, and stretching the carrying capacity of ecosystems is a global challenge. It is, therefore, essential to develop a holistic system that considers the balance between food security and the use of biofuel to reduce gas emissions that benefits local socio-economic development. Life cycle sustainability assessment, optimization, agent-based modelling, and simulation are the tools used to build an integrated system modelling framework applicable to the resource–food–bioenergy nexus (Avraam et al., 2021; Guo et al., 2020). Case studies in the Philippines and Africa revealed the great potential of untapped biomass, including agricultural waste and non-food biomass grown on marginal lands. Case studies highlight how an integrative modelling framework can be applied to address multi-level questions, with considerations of decision-making at various levels, which contribute to an overall sustainability goal (Guo et al., 2020).

In the Philippines, sugarcane is a more feasible energy crop for bioethanol than corn and cassava, but a coconut is a viable option for biodiesel. Reliance solely on sugarcane in promoting the country's bioethanol policy will not be adequate considering the level of sugarcane production (Maruyama et al., 2009). Recent trends on sugarcane production and biofuel conversion for the generation of electricity are studied, looking into the barriers and challenges for the development of biofuel strategies to provide an insight on the current status and future projection of biofuel from sugarcane (Mandegari et al., 2019).

## 4 Strategies to Manage the Pressure to Address Food Security and Biofuel Sufficiency

In Southeast Asia, emerging economies face considerable challenges in addressing the upsurge of cars and motor vehicles that impact air quality, traffic, energy security, and GHG emissions. Bakker et al. (2017) made a comparative analysis on the approach and status of sustainable, low-carbon transport policy in ASEAN countries and identified differences and similarities. Their findings revealed that there is much more effort required to enable a transition to a transport system compatible with long-term climate change and sustainable development targets. In the Philippines, government agencies and coconut farmers have lobbied for an increase in biodiesel blend from 2 to 5% in order to boost coconut oil utilization in domestic diesel and support the local industry. Piranfaret al. (2019) determined the net economic impact of higher-blended biodiesel on the biofuel supply chain and showed that benefits outweighed the losses and that the rising oil prices may encourage higher bio-content and better prices for the farmers.

Most of the world's poor people live in rural areas engaged in agriculture. Therefore, biofuels expansion may pose significant challenges for poor small farmers in the developing world. Strategies to provide infrastructure support for access to and from the market can hasten rural development. Research on new technologies, such as pelletization and drying, might be a promising way of reducing transport costs for biofuels, but more research on the applicability of these systems in developing countries is needed (Peskett et al., 2007). Renewable energy from tree biomass is being eyed to offer a solution to limited energy supply. A component of the green energy generation project is to assess the biomass potential of fast-growing tree plantation species in the region at various ages to determine the sustainability of a biomass-based green energy generation (Sarmiento & Varela, 2015). Falcata (*Paraserianthes falcataria* Nielsen) and Mangium (*Acacia mangium* Willd.) have the biggest potential to supply the biomass requirement of the green energy plants.

## 5 Understanding the Biofuel Landscape Supporting Food Security and Biofuel Sufficiency

• The Agri-forestry Continuum

In the early discovery of biofuels and bioenergy, agriculture and forestry were the essential sectors involved in the production of the required biomass in support of clean energy options (Ambaye et al., 2021; Benjamin et al., 2021; Guo et al., 2020). Biomass provides around 14% of the global energy consumption, with 25% of bioenergy consumed by developed nations for industrial use and 75% used up by developing nations for household use in general (Xu et al., 2018). Xu et al. (2018) reported that biomass from forestry and agriculture is the only carbon source that can be reused in the form of clean (decarbonized) energy and fuels as well as useful biochemicals through thermochemical and biological means of conversion. Particularly, the first-generation biofuels make use of a lot of materials from edible crops, which had eventually become a global concern as such material sources competed with food security—an internationally recognized strategic welfare objectives (Ambaye et al., 2021; Dalena et al., 2019; Guo et al., 2020). Agriculture and forestry provide the agroecosystems that nurture the cellulosic biota (Antar et al., 2021), which through time have also been learned to be mergeable in certain farming systems. In the case of producing biosynthetic natural gas (bio SNG) in the Republic of Ireland, associated biomass is scrutinized via the moisture content of the materials as moisture content is a factor in the gasification process-preferring the residue waste from agriculture and forestry (among others) over the biomass from aquatic sources (e.g., algae), because the gasification process for biomass has to be with low moisture content as in the plant and wood residue waste (Singlitico et al., 2018).

The work of Gingrich and Krausmann (2018) has also demonstrated the specific dynamics in the energy fluxes involving the agriculture and forest ecosystems and the society in the metabolism of biomass for energy production. Such ecosystems are highlighted in the fluxes of bioenergy as obviously rich sources of biomass to be processed into biofuels and other bioenergy forms for the generation of clean/decarbonized renewable energy (Antar et al., 2021; Gingrich & Krausmann, 2018). However, issues with the biomass from these sources also encompass environmental footprints. For instance, while woody residues from forest ecosystems as biomass resources conform to food security, these materials may endanger the forest ecosystem's health, as in the issue of the removal of forest floors that cause losses in soil carbon and nitrogen (James et al., 2021). This is relatively true to the agricultural residues as a soil conditioning agent, which when removed from the field for bioenergy, the opportunity to restore soil health is diminished due to the diminished availability of organic matter in the field. The reuse of biomass from the forests thus needs to be looked at the spectrum of sustainable origins like the planted forests in the Philippines and/or perhaps the reuse of forest thinnings or of protection mechanisms from disastrous wildfires (James et al., 2021). In fact, the forestry sector is identified in Germany as a significant contributor to the development of the bioeconomy with the utilization of timber biomass (Purkus et al., 2018). Current research has in mind the protection of the aforementioned ecosystems; however, as both are important life support systems besides their bioenergy contribution, such that their current environmental concerns (water availability, soil health, land conversion, and biomass use intensity) are addressed properly with R and D innovations to continue producing biomass for the availability of clean energy (Dalena et al., 2019).

- Sustaining the Land that Supports Food and Fuel Productivity

The land is a critical resource, particularly in the food–bioenergy–environment nexus (Pulighe et al., 2019). Most of the biomass sources for biofuels and/or bioenergy are land-based, especially those which are used for the first-, the second- and the third-generation biofuels (Poláková et al., 2021). Research on the exploration of alternative sources of biomass has commenced exploratory studies to expand the source options of the said bioenergy material, which also coincide with the research and development efforts to expand the capacity and versatility of conversion processes with integrated biorefineries (Awasthi et al., 2020). Poláková et al. (2021) have demonstrated the expansion of biomass sources for biogas by means of utilizing the less-favoured areas in the production of the biomass requirement that is focused on maize, grass, and sorghum for the case of the Czech Republic in Europe. The less-favoured areas have been utilized in the hope of easing the pressure on land for food production, particularly with maize in the Czech Republic (Poláková et al., 2021). This case is similar to that of Pulighe et al. (2019) and of Schröder et al. (2017), which both see the use of the marginal lands as an important option in order to secure bioenergy sources without compromise with the food security objective as well as other environmental issues associated with land-use changes. In England, French (2019) reported similar efforts with the exploration of grassland conservation areas for biomass production, which are characterized to be of high diversity and high biogas yield, although a bit less in biogas yield compared to the miscanthus grown in fields in England. The biomass in the grasslands under study by French (2019) has been noted to have 50% lower lignin content than the other bioenergy crops but have 160% higher biogas yield per ton of dry matter compared to the cereal crops and the crop residues in the fields of England.

Moreover, the circular bioeconomy concept guides the other strategies to sustain the land resource on the aspect of biomass production. Awasthi et al. (2020) looked into the efficiency of the waste valorization and the performance of the biorefineries to determine the development measures of improving further the efficiency of the biorefinery technology. In the utilization of marginal lands for biomass production, Schröder et al. (2017) recommended being keen on the management practices for the optimization of biomass yield from these lands, in which productivity improvement innovations may consider land remediation measures to reverse the effects of unsustainable and land-degrading practices. In the study of Clarke et al. (2019), who used GIS and life cycle assessment (LCA) in the analysis of land-use changes as influenced by bioenergy in Ireland, production operations such as land preparation and harvesting are found to contribute significantly to field emissions (e.g., greenhouse gases) as well as the use of synthetic fertilizers. The replacement of these synthetic fertilizers with biogenic fertilizers is found to enhance the ecological benefit with lesser GHG emission, according to Clarke et al. (2019). Although land productivity is not connected directly with GHG emission, however, in sustainability parlance, biogenic fertilizers are the ones advocated. This biogenic type of fertilizers is consistent also with the promotion of conservation agriculture to sustain the production of biomass resources, which has been noted in the work of Schröder et al. (2017) regarding the use of marginal lands for biomass in Europe. Conservation agriculture is pointed out in the work of Vicarro et al. (2019) as a strategy to contribute to sustaining the production of biomass for bioenergy with crop diversification, crop rotation, and minimum tillage as relevant practices to conserve the land resources for the food–bioenergy–environment nexus. This, however, is realized the need for robust information and policy support to work effectively (Helliwell, 2018; Karabulut et al., 2018).

## 6 Agriculture 4.0: Its Implications to Food Security and Biofuel Sufficiency

- Coping with the Requirements for Food and Fuel by Using High-yielding Crop Varieties

With the determined pursuits of bioenergy objectives and bioenergy's increasing demand for sustainable development, the sources of the required biomass have been expanding to cover non-agricultural and aquatic areas to generate the required material for bioenergy (Dalena et al., 2019; Kurczyński et al., 2021; Soliño et al., 2018). While forest, non-crop-based and aquatic biomasses have been studied and examined for their yield and biorefining/conversion implications (Dalena et al., 2019; Kurczyński et al., 2021), the exploration of agri-based biomass sources has continued to discover crop varieties that are high-yielding in biomass. Firouzi et al. (2021) discussed their 10-point criteria in the evaluation of the candidate biomass sources as important to look into and understand (1) the capability to provide sufficient buffer materials in place of the non-renewable energy sources, (2) the capability to provide technical job opportunity, (3) the advantage of using a particular biomass source vis-a-vis other sources including the non-renewable ones, (4) the difficulty of converting them into bioenergy, (5) the relative costliness of the conversion process, (6) the relative reusability of the biomass, (7) the relative costliness/cost-effectiveness of the biomass supply, (8) the associated environmental issues of the biomass, (9) the capability of the biofuel production process to adapt with attitude and production capacity of biomass suppliers, and (10) the self-reliant energy available to the biomass producers. These criteria provide a scenario of the viability of the bioenergy options available to a society, should it decide to produce bioenergy by harnessing available potential sources (Firouzi et al., 2021). Firouzi et al. (2021) have tested their criteria with 11 potential sources, wherein the most viable sources are associated with the second-generation biofuels like the "municipal solid waste and sewage, forest and wood-farming wastes, and livestock and poultry waste" in the area studied (Guilan Province in Northern Iran).

Other means of verifying the viability of biomass production with respect to other conflicting uses and objectives are demonstrated in the work of Li et al. (2020) relative energy–food–water–land nexus and agricultural systems with uncertainty as well as that of Karabulut et al. (2018) with the life cycle assessment of the and synthesized matrix for food security evaluation. For land-based non-woody sources of biomass, an increasing number of crops have been studied to account properly for their biomass productivity for the viability of the bioenergy options vis-à-vis other welfare objectives (food security and environmental health). Dalena et al. (2019) reported looking for feedstocks beyond the first- and second-generation sources, of which many are yet under study. In addition to maize, soybean, sugarcane, agave, rapeseed, legumes, hemp, and miscanthus as feedstocks, among others (French, 2019; Mercure et al., 2019), Crambe (*Crambe abyssinica* Hochst ex R.E. fries) and camelina (*Camelina sativa* L. Crantz) are found to be promising for the integrated/multiproduct biorefineries, especially that they non-food crops of high oil content under *Brassicaceae* family thriving well in low-quality soils even with reduced-tillage farming practices (Krzyżaniak & Stolarski, 2019). French (2019) had investigated the grassland species to find tall grass species (> 100 cm) (e.g., reeds (*Phragmites Australis*), Orchardgrass (*Dactylis glomerata*), Yellow Oat Grass (*Trisetum flavenscens*), and Giant Fescue (*Festuca gigantea*) as potentially high-yielding in biogas. In the Netherlands, potato by-products from a potato processing industry and sugar beet as a major sugar crop have been utilized sufficiently for biofuels (e.g., ethanol, biogas, and hydrogen) year-round (Moretti et al., 2021). Kurczyński et al. (2021) reported an interesting finding on the biofuel from babassu palm oil-based butyl esters as performing much better than that of rapeseed oil in terms of GHG emissions. Babassu palm biomass has high potential, particularly in the generation of electricity (Kurczyński et al., 2021). However, using the criteria of Firouzi et al. (2021), important second-generation biofuel sources turn out to come from municipal waste, forest/wood waste, and farm animal wastes in Guilan Province in Northern Iran.

- Turning food waste into a valuable biofuel resource

Research on food waste valorization has picked up speed over the years, changing the general outlook of food wastes gradually as useless and bound-for-trash-site materials in the process. Food waste has become an alarming issue over time with its tremendous generation that is increasing exponentially with a global population (Karthikeyan et al., 2018; Ma et al., 2018). Households are not only responsible for this but also the key players in the middle of the agri-food chain (e.g., food processors, food packers, and distributors) (Srivastava et al., 2021). The Food and Agriculture Organization (FAO) had reported that along the food supply chain, one-third of the food produced is wasted globally, particularly at the point of the end consumers (households, restaurants, and canteens), which is a dominant scenario in the developed and the developing countries of Asia, the North and South America, Europe, and Australia (Melikoglu, 2020; Philippidis et al., 2019; Socas-Rodríguez et al., 2021; Strazzera et al., 2018). The reuse of food waste is an ambitious strategy towards a tremendous reduction of waste generation across the world, particularly halving food waste generation per individual (Philippidis et al., 2019). A circular bioeconomy has been around for such purpose (food waste reuse and reduction) with designs to regard food waste as a valuable resource to an important clean bioenergy option for a circularizing society (Awasthi et al., 2020; Karthikeyan et al., 2018; Sharma et al., 2021). Tremendous volumes of food wastes across the world have caused a huge problem that contradicts the global sustainability initiative (Srivastava et al., 2021; Strazzera et al., 2018).

Food wastes undeniably release emissions to the atmosphere, increasing the heat or exacerbating the heating of the atmosphere in the process besides water pollution and other adverse environmental effects (Kannah et al., 2020). The valorization process can utilize the energy potential contained in this kind of waste, which benefits society smartly in the long run as a source of clean energy and a way of reducing its build-up in the environment (Kannah et al., 2020). Although quite diverse in material types, food waste's bioenergy potential is due to its suitable physical and chemical properties that can produce a wide range of bio-based products such as biofuels (e.g., biomethane, biomethane, biohydrogen, and biodiesel), bioplastics, organic acids, enzymes, single-cell proteins, biofertilizer, biochar, and other useful biochemicals, all of which are extracted from the food waste's highly degradable "natural fibres, carbons, proteins, lipids, vitamins and minerals" (Kannah et al., 2020; Karthikeyan et al., 2018; Srivastava et al., 2021). However, the heterogeneity of food waste composition poses a substantial challenge in its conversion. Socas-Rodríguez et al. (2021) reported the increasing attention of the EU on the reuse of wastes from vegetables, meat, beverages, fruits, sugar, seafood and fishery products, among others, for bioenergy. Several intermediate products can be derived from food waste, such as volatile fatty acids and cellulose, which require specific technological processes (Srivastava et al., 2021; Strazzera et al., 2018). Such required variety of technological processes is a substantial challenge that needs to be checked with the requisites of viability via the economics of undertaking bioenergy with food waste (Ma et al., 2018). With the increasing volume of this kind of waste across the world, there is a bright prospect ahead to key it in as an important energy resource in the future, which is not going to compromise food security with the useful compounds (e.g., biofertilizers and biochar) also produced for agriculture (Kannah et al., 2020; Negri et al., 2020; Sharma et al., 2021).

## 7 Conclusions

The expansion and intensification of biofuel production is a global challenge as this results in land-use conversion and disruption in the normal socio-environmental system. The rural areas where the poorer sector lives and earn a living through farming are generally affected by the biofuel expansion. Nonetheless, with the biofuel policies anchored on sound science-based information and scenarios, the promotion of biofuels can address the sustainability requirements of enhancing the economic gains among players, reduction in gas emissions, and social equity for all, including the farmers in rural settings. Undertaking a holistic approach through applying the concepts of industrial symbiosis and circular economy may offer potential solutions to sustain the biofuel economy without putting at risk the supply of food. Recycling wastes and residues from the farm for biofuel generation are plausible ways to optimize the overall productivity of agricultural lands towards addressing the requirements for food and biofuel. The adoption of Smart Agriculture/Agriculture 4.0 for the management of the entire agri-food supply chain from pre-production to post-harvest stage has a strong influence in sustaining the biofuels endeavour without disrupting the food supply.

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# Biofuels in Low Carbon Economies and Societies

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## 1 Introduction

### *1.1 Depletion of Fossil Resources and Global Warming*

According to the most recent forecast, a world oil reserve equivalent to 1,700,803.80 million barrels of oil was estimated (Eurostat, 2021; National Center for Hydrocarbons Information (CNIH), 2013; National Hydrocarbon Commission (CNH). Currently, there is a high dependency on fossil resources for energy and commodities production. Oil derivatives continue to be the main source of energy consumption worldwide, representing 31% of the energy consumed, followed by coal with 26% and gas with 23% of energy in 2019. (World Bank Group, 2021). Fossil fuels have been abundantly extracted and used by humanity in recent centuries. Approximately, 80%, 50%, and 30% of the total existing reserves of coal, gas, and oil, respectively, should remain underground in order to limit the greenhouse effect derived from their exploitation, which will increase the global average temperature of 2 °C (Pellegrini et al., 2021).

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Carbon dioxide ($CO_2$), nitrous oxide ($NO_2$), ozone ($O_3$), and methane ($CH_4$) can emit and absorb infrared radiation, resulting in the greenhouse effect, which makes the planet habitable with an average global temperature of 14 °C. Without this effect, the earth's temperature would decrease to −19 °C, preventing the development of life on earth. However, the rapid expansion of industry and agriculture based on the use of fossil fuels consumption has increased the levels of these compounds in the atmosphere (Hu et al., 2021). Transformation of the energy sector towards a renewable alternative relies on the substitution of oil products providing environmental, social, and economic benefits. The main sources involved in this transformation are biomass, solar energy, wind, and biofuels.

## *1.2 The Circular Economy Solution*

The predicted 9 billion world inhabitants by 2050 will increase food and feed demand resulting in a proportional increase in agricultural wastes. Over the last decade, agricultural wastes accounted for a potential of 90 Million-ton oil equivalent (MTOE), which is considerably higher than any other existing by-products such as wood chips (57 MTOE) or municipal wastes (42 MTOE). The residues generated in the agricultural and livestock activity have been increasing in recent years due to the establishment of new farms and the larger agricultural exploitations. In most cases, insufficient management of these residues results in environmental problems on a global scale, such as soil and water pollution or indirect greenhouse gas (GHG) emissions. Currently, waste can be considered a resource when used to generate energy and high-value products. The conversion of agricultural, livestock, and forestry wastes into bioenergy is currently used to reduce consumption and dependence on fossil fuels. Intensification of this material conversion is regarded as the cornerstone of sustainable development for the next decades. Agricultural wastes present advantages over other wastes given their inherent characteristics: homogeneity, well-known processing techniques, and ubiquity. The key to the circular economy is using waste as an energy source for the generation of biofuels and the production of high-value chemical compounds. In some cases, a combination of the waste streams is necessary to establish the sustainability criteria needed (Song et al., 2020).

## *1.3 Energy Consumption*

Energy consumption is normally divided into sectors being transport, buildings, electricity, and industry the main divisions. In the European Union (EU) countries, in 2014, the transport sector consumed 33% of total energy consumption. Being 94% of the energy consumed is derived from oil. The transport sector generates 25.5% of the EU's greenhouse gas (GHG) emissions (European Commission, 2021). This sector is essential for the development of the economy. Transport consumes a large amount of energy and is powered mainly by fossil fuels due to the widespread use of heat engines, based on the combustion of gasoline, diesel, compressed natural gas (CNG), and liquefied petroleum gas (LPG) (Zong et al., 2020). The renewable energy sources that gradually replace fossil fuels in the transport sector are biofuels (biodiesel, bioethanol, biomethane, biobutanol, and biohydrogen) and electricity. However, electricity production can involve both renewable and non-renewable sources. Electricity-based systems are easily connected with renewable energy production. However, the proportion of transport powered by electricity is very low compared to propulsion with fuels. The use of electric motors for transport is well-implemented in rail transport. On the other hand, road transport is responsible for the majority of the energy demand of transport. In this scenario, the integration of biofuels in the transport sector is necessary to completely substitute fossil fuels (Neves et al., 2017).

Buildings represent an average energy consumption of 30% of world energy consumption, and a large increase is expected in the future. In the USA, energy consumption in 2019 by the residential and commercial sector was approximately 6.24 TWh, which is equivalent to 28% of end-use energy consumption. Such high energy consumption could be reduced with a slight improvement in the energy efficiency of buildings. (Dong et al., 2021; Luo et al., 2021).

Finally, emerging economies are the ones in the focus of study, as they have experienced rapid economic growth and high energy use and are deeply affected by globalization. As the largest developing economy for world growth, China accounted for 24% of world energy consumption, with an increase of 34% of total energy consumption worldwide in 2018 (Acheampong et al., 2021). Implementation of renewable sources presents an unequal development. In 2019, renewable energy accounted for 19.7% of the energy consumed in the EU-27, just 0.3% below the 2020 target of 20%. In the USA, approximately 12% of energy production was based on renewable energy (Lahiani et al., 2021). Initiatives to foster the renewable sector have been launched in Europe, China, Brazil, and USA. This includes incentives, tax reduction, and soft loans (see Sect. 4).

## *1.4 Biofuels Role in the Transformation*

Electrification based on renewable sources is a critical element in achieving the UN Sustainable Development Goals (SDGs) (United Nations, 2019) and focuses on various global development initiatives. Currently, there is an installed power of 142 GW for photovoltaic solar energy, 80 GW for wind energy, 32 GW for hydroelectric energy, and 12 GW for other renewables, according to data from the International Energy Agency (IEA). Currently, there is an installed power of 142 GW for photovoltaic solar energy, 80 GW for wind energy, 32 GW for hydroelectric energy, and 12 GW for other renewables, according to data from the International Energy Agency (IEA). Wind and solar energy are highly dependent on meteorology, resulting in high uncertainty of the adjustment between energy supply and demand (Abedinia et al., 2019). Under this scenario, it is necessary to dispose of other renewable energy sources independent of environmental factors or seasonality. Biofuels produced from agricultural waste can provide energy products compatible with liquid and gaseous biofuel consumption (Kurczyński et al., 2021; Millo et al., 2021).

Biofuels can be used in transport, industry, and heating in the pure form blended with fossil derivatives. Therefore, the introduction of biofuels provides a transition for sustainability in transport, industry, and heating. Biofuels reduce air pollution and greenhouse gas emissions. Therefore, the replacement of fossil fuels with biofuels reduces the global warming effect. The production of biofuels is considered $CO_2$ neutral, given that carbon embedded comes from atmospheric $CO_2$ previously fixed from biomass.

Furthermore, biofuels have a greater ability to reduce greenhouse gas emissions during their production than electricity generation, according to some life cycle analysis. (Scovronick & Wilkinson, 2013). In this context, it is necessary to combine electrical energy from renewable sources with the use of biofuels. According to data from the International Energy Agency (IEA) 2013, oil consumption will decline from its global market share by at least 5% by 2040. This reduction will be based on a continuous substitution by renewable electricity and biomass energy products.

A large part of the biomass is generated to provide heat and electricity. However, the need to replace fossil fuels in transport vehicles and engines for other purposes has led to a continuous increase in the production of biofuels. Liquid biofuels such as bioethanol and biodiesel are being used more frequently to replace fossil fuels in the transportation sector. These biofuels are essential in mitigating climate change, revitalizing agricultural economies, and achieving security of energy supply with low $CO_2$ emissions (Løkke et al., 2021a). In recent years, from 2010 to 2017, biofuel production increased from 16 billion liters to 143 billion liters (WBA, 2018. http://www.worldbioenergy.org), with bioethanol being the main responsible for this growth.

Despite high political support and incentives for electric vehicles, their market acceptance is not enough to meet the decarbonization targets, and large volumes of direct renewable fuels will be required to reduce the environmental impact of the light vehicle fleet (Costa et al., 2021). Electric vehicles involve environmental problems such as emissions from batteries manufacture and consumption of limited available resources such as lithium. Besides this, the production of part of the energy used in recharging could involve non-renewable sources. The production of batteries for electric cars produces between 150 and 200 kg of $CO_2$/kWh. (Agusdinata et al., 2018; Panoutsou et al., 2021).

## 2 Biofuels

Biofuels are substances derived from renewable biomass that mainly includes liquids bioethanol, biodiesel, and biobutanol or gases biomethane and biohydrogen. Biomass feedstock can be produced from various renewable sources such as agricultural and forestry residues, grains, starch crops, vegetable oils, waste oils and animal fats, dedicated energy crops, algae, and others. (Paul et al., 2019; Pishvaee et al., 2021; Yue & You, 2016).

### 2.1 Bioethanol

Bioethanol is a fuel capable of replacing gasoline produced from different kinds of biomass feedstocks. Unlike oil derivatives, ethanol is oxygenated, thus potentially reducing particulate emissions in internal combustion engines. It presents a higher octane number and lower cetane number, wider flammability limits, higher flame speeds, and higher heats of vaporization than gasoline. Bioethanol can be produced from lignocellulosic biomass, starchy materials such as corn, wheat, cereals and raw materials containing sucrose, for instance, sugarcane and beet (Patni et al., 2013). Ethanol produced from lignocellulosic wastes such as agricultural or forest by-products is the most sustainable option in resource consumption and lack of competence with food and feed production. According to the most recent life cycle analysis reported, lignocellulosic ethanol presents a significantly reduced carbon footprint (Capaz et al., 2021; Holmatov et al., 2021). Lignocellulosic materials contain biopolymers that can be transformed into bioethanol through an intense combination of processes (pretreatment, hydrolysis, fermentation, and distillation).

During the pretreatment, vegetal materials are ground to reduce particle size. Then a specific pretreatment are applied, resulting in a disaggregation of polymers such as cellulose and hemicellulose. Different types of biomass pretreatment are applied depending on the nature of the biomass. Proper pretreatment to prepare biomass for cellulose hydrolysis is essential for bioethanol production. The pretreatment methods currently exist are: steam processing, grinding, hot water, hydrolysis, acid treatment, alkaline treatment, and others (Vohra et al., 2014). Among these methods, the most widely used is alkaline pretreatment due to its high efficiency in polymer disintegration and relatively simple process applied in mixed tanks. NaOH or other basic solutions selectively remove lignin without leaving carbohydrates containing glucose and pentoses (cellulose and hemicelluloses) exposed to the subsequent enzymatic degradation. These pretreatments increase the porosity and surface area of the vegetal particles, then the efficiency-enhancing hydrolysis process (Kim et al., 2016).

Former lignocellulosic processes were based on the hydrolysis of polymers containing sugars by adding acids (strong or diluted solutions of HCl, $H_2SO_4$, or others). Recent advantages based on the use of fungi enzymes provide higher hydrolysis yields. Although the structural composition of lignocellulosic biomass provides resistance to degradation, fungi enzymes present specific mechanisms for sugar solubilization. Pretreatment and enzymatic hydrolysis involve a significant amount of the costs of the lignocellulosic pretreatment. Therefore, special attention must be devoted to the design of these critical steps (Manzanares, 2010).

The aqueous solution obtained after the hydrolysis treatment is rich in sugars (six and five carbons) transformed into ethanol by microbial fermentation mediated by yeast or bacteria. Recent advances in engineering and biotechnology try to integrate most processes into a single unit. The consolidated bioprocessing (CBP) combines the three biologically mediated steps (cellulose production, enzymatic hydrolysis, and microbial fermentation) in a single operational tank (fermenter). CBP has exceptional potential to provide an innovative solution for the biological conversion of cellulosic biomass to ethanol. CBP implementation requires microbes that can produce functional cellulase enzymes while generating ethanol with high yields and concentrations. Therefore, subsequent energy cost in distillation is considerably reduced (Fuess & Garcia, 2017), (Fan, 2014). Reduction of steps enhances biotransformation of lignocellulosic materials since biological inhibitions of enzymes and yeast are avoided (Vohra et al., 2014).

### *2.2 Biodiesel and Hydrogenated Vegetable Oils*

Oleaginous crops accumulated lipids with a very high energy density. After simple mechanical extraction, oil containing these lipids is produced. Unfortunately, unmodified commercial vegetable oils are too viscous (10–20 times higher than diesel fuels) to be compatible with modern direct injection (DI) diesel fuel systems and engines. The engine technology required for this purpose is cost-effective only for large diesel engines used in ships or heavy trucks. In smaller cars and trucks, chemically altered vegetable oils are used (Paul et al., 2019). This modification consists of a viscosity reduction achieved by transesterification or hydrogenation, resulting in conventional biodiesel and hydrogenated vegetable oils, respectively.

In recent years, biodiesel production has undergone several advances, evolving from the conventional base-catalyzed transesterification process with virgin vegetable oils as feedstock to advanced processing strategies using inedible products (e.g., microalgae, oilseeds, and microorganisms), as well as waste raw materials (e.g., used oils and fats). Depending on the raw materials used to produce biodiesel, several configurations of biofactory have been implemented. Recent installations based on multiple waste processing are flexibly designed in order to operate under different feedstock supplies.

The process for obtaining biodiesel starts with the extraction of the oils. In the case of oleaginous seeds pressing processes are commonly applied (Koçar & Civaş, 2013). After the oil is obtained, ultrasonic pretreatment is applied to promote homogenization of the product required for the transesterification process. The mild reaction conditions of the transesterification require the removal of free fatty acids from the oil by refining or pre-esterification to avoid soap formation during the alkaline catalyst (Shatesh Kumar et al., 2020).

The refined oil is then subjected to a transesterification reaction by mixing the oil with alcohol (methanol or ethanol). The transesterification of fats and oils is the most conventional process for the manufacture of methyl esters, by which triglycerides react with primary alcohol, giving rise to methyl esters and glycerin. The behavior of methyl and ethyl esters is very similar, but it has been found that methyl esters provide slightly higher potency as fuel than ethyl esters and lower viscosity (Almasi et al., 2021). Apart from this, methanol has a lower cost and reacts fast and at a low temperature. On the other hand, methanol is normally produced using natural gas as a substrate, resulting in a procedure reliant on fossil resources. Triglycerides are transesterified batch-wise or continuously using multi-pass reactors at atmospheric pressure and a temperature of approximately 60–70° C with an excess of methanol and in the presence of an alkaline catalyst such as sodium methylate or potassium hydroxide (Mumtaz et al., 2017; Pruszko, 2020).

The mixture can settle at the end of the reaction. The lower glycerin layer is removed, while the upper methyl ester layer is washed with water to remove entrained glycerin. Biodiesel is obtained from this process for energy use, and glycerin is used in the food and cosmetic industry (Atadashi et al., 2011; Gojun et al., 2021).

Hydrotreated Vegetable Oils (HVOs), commonly known as renewable diesel and Hydroprocessed Fatty Acids and Esters (HEFA), are produced by hydroprocessing oils and fats. Hydroprocessing is an alternative process to the esterification to produce diesel from biomass. (Shatesh Kumar et al., 2020). Catalytic hydrotreating of vegetable oil is considered an alternative technology that also employs existing refinery infrastructure. Today, HVO biodiesel is produced from waste and residual fat fractions derived from the fish and slaughter industries, vegetable oils, tall oil, pyrolysis oil, and non-food grade vegetable oils. Used vegetable oils or cooking oils are initially pretreated and purified before being co-processed with diesel intermediates during the crude oil refining process to produce an HVO-containing fuel. Biodiesel from HVO can be produced in a separate hydrogen treatment plant, in most cases using waste, residual oils, and animal fat feedstocks rather than oil crops. (Mohiddin et al., 2021). In this process, hydrogen is used to remove oxygen from vegetable oil triglyceride molecules and to split triglycerides into separate chains, creating diesel-like hydrocarbons (di Blasio et al., 2022). A range of biofuels can be produced from HVO, including advanced biodiesel, naphtha, and aviation fuels. In the long term, the production of pure HVO offers more alternatives, as it can be used as a direct fuel or jet fuel, or it can even be mixed with off-spec diesel to improve its characteristics (Tsita et al., 2020). HVO allows appreciable reductions in NOx, PM, HC, and CO emissions without any change to the engine. (Dobrzyńska et al., 2020).

## *2.3 Biomethane*

Biomethane is a versatile renewable fuel obtained from refining the main product of the anaerobic digestion (biogas) through the elimination of unwanted compounds generated in its production, such as $CO_2$, $H_2S$ $H_2O$ mainly. To produce biogas, different sources of organic matter are used, such as sewage, landfill waste, solid urban, agricultural or livestock waste. Mixtures of different materials are used to enhance biodegradability and compensate insufficiencies of elements for the anaerobic digestion (f.i. wheat straw and dairy manure are mixed to create an optimum substrate in terms of carbon and nitrogen). (Deublein & Steinhauser, 2008). Materials of agricultural origin are the most widespread feedstock for biomethane production.

In 2019, 140 million tons of animal manure and 43.6 million tons of agricultural waste were generated worldwide (FAO, 2019).

The biomethane is produced spontaneously by methanogenic *archaea* in storage areas of livestock waste (soils fertilized with manures and ponds used for storage of animal wastes), resulting in emissions of $CH_4$, $N_2O$, and $CO_2$. (Liu et al., 2021). Control and reduction of these emissions have been pointed out as a priority in the fight against climate change. (Liu et al., 2021). By introducing anaerobic digesters in pig and dairy farms, it is possible to recover biomethane produced from organic matter degradation. (Liu et al., 2021). Besides this, effluents from digesters (digestates) can be used as high-quality fertilizers reducing the demand for synthetic fertilizers based on nitrogen salts, which require important amounts of energy and fossil fuels consumption during the manufacture. In addition, digests provide an important amount of phosphorus which is considered a limited resource (Liu et al., 2021).

The complete anaerobic digestion process takes place in a combination of four enzymatic and microbial processes called hydrolysis, acidogenesis, acetogenesis, and methanogenesis, in which different microbial species decompose organic matter in the absence of oxygen, generating biogas (Achinas et al., 2020). In the case of vegetal wastes, particle size reduction is required in order to promote biodegradation. The most widespread pretreatment methods applied in biogas production are thermal, mechanical, chemical, ultrasonic, liquid evaporation techniques, biological and a combination of different methods. Among these, a better performance, in terms of biogas produced per unit of biomass, is thermochemical pretreatments at a temperature below 100° C and atmospheric pressure (Kowthaman et al., 2021). The results of biomethane production using heat treatments are 154.9 ml/gSV (Mirko et al., 2021) and thermochemical 203.04 ml/gSV (Kumar et al., 2021b). Ultrasonic pretreatment provides a biomethane production of 141.9 ml/gSV as tested (Mirko et al., 2021). Other methods that are applied to eliminate the aggregation of agricultural wastes are biological and mechanical treatments. Biological methods involve a minimal input of energy and are based on the incubation of biomass with selected microorganisms that produce extracellular enzymes that modify biomass. Some tests with fungi have provided 339.31 ml/gSV and with thermophilic lignocellulolytic bacteria 171.70 ml/gSV (Kumar et al., 2021b). The most used mechanical treatments are milling and extrusion. With grinding 197 ml/gSV are obtained, and with extrusion 227.30 ml/gSV. (Kumar et al., 2021b), chemical treatments such as alkaline pretreatment have been used mainly for lignocellulosic materials, reaching a maximum yield of 29.1%. The function of the alkaline treatment is the saponification of the materials and the cleavage of the lignin–carbohydrate bonds, increasing the porosity and the surface. Furthermore, the residual biomass's alkaline pretreatment could help reduce the pH level in the acidogenesis phase. A significant degradation occurs in rice straw pretreated with $Ca(OH)_2$ under optimal conditions, reaching a methane yield of 225.3 ml/g VS. Improved solubilization of lignin and polysaccharides in the substrate was achieved using NaOH and Ca $(OH)_2$ with 0.5–30% w/w at a pretreatment temperature of 15–160 °C (Kowthaman et al., 2021).

The biogas obtained during anaerobic digestion contains the following percentages: $CH_4$ (40–70%), $CO_2$ (35–55%), $H_2S$ (0.1–3%), a small amount of moisture and other trace gases (Brancoli & Bolton, 2019). It should be mentioned that the presence of sulfur compounds in a significant amount damages vehicle engines and boilers designed for conventional natural gas due to their destructive nature and therefore limits the direct application of biogas as a transport fuel on grid injection. Therefore, it is necessary to purify the biogas to obtain enriched biomethane (biofuel) from biogas generated in anaerobic digestion.

Different technologies for eliminating $CO_2$, $H_2S$, $H_2O$, $O_2$, $N_2$, siloxanes, and halogenated hydrocarbons are known as biogas upgrading. Due to the increase in the biomethane market and the increase in biofuels for the transport sector, to the detriment of fossil fuels, there are numerous biogas upgrading plants. Germany and Sweden are the countries with the highest number of biomethane generation facilities. Among the $CO_2$ removal technologies, the most used commercially is pressure washing, representing 41% of the plants, followed by chemical washing representing 22%. PSA adsorption systems accounted for 21%. The membrane separation represents 10% of the plants. The organic solvent wash represents 6%. Cryogenic separation forms 0.4%. And finally, the lesser-known biogas photosynthetic enhancement technology with microalgae (Adnan et al., 2019; Nguyen et al., 2021; Niesner et al., 2013).

The water absorption techniques are based on the solubility of the gases contained in the biogas in the water. Washing with water is used as an improvement technique and as a pretreatment for the elimination of $H_2S$. The main limit of pressure washing is that significant plant size is required to achieve a high final methane concentration (Prussi et al., 2019). This method involves reversible reactions between the absorbed substances and the solvent. The most common solution for biogas improvement is based on amines: diethanolamine, monoethanolamine, methyldiethanolamine, and piperazine. The amine scrubber consists of an absorption tank, where the $CO_2$ is absorbed from the biogas (operating at 20–65 °C and 1–2 bar), followed by an extractor in which the $CO_2$ is released by heating the stream. Chemical scrubbing (CSC) with amine allows for achieving a highly concentrated $CH_4$ biomethane stream > 99%. CSC requires a pretreatment step to remove $H_2S$. The CSC is characterized today by high operating and investment costs. (Prussi et al., 2019).

Pressure switch adsorption (PSA) technology is a technique based on the selective adhesion of one or more components of a gaseous mixture on the surface of a microporous material; the material for biogas upgrading is usually equilibrium-based adsorbents. The adsorbent pores should allow easy penetration of the $CO_2$ molecules while the larger $CH_4$ molecules are filtered out. Molecular sieve materials such as zeolites and activated carbon are commonly used as adsorbent materials for biogas enhancement (Prussi et al., 2019).

Membranes are permeable barriers specifically designed to be selective for specific molecules. The process parameters are the different molecules' relative concentration, pressure, temperature, and electrical charges. Three types of membranes are typically used in the market: polymeric, inorganic, and mixed matrix membranes. Inorganic membranes have several advantages compared to polymeric membranes, mainly due to their higher mechanical strength, chemical resistance, and thermal stability. The current trend in industrial applications is to use mixed matrix membranes. In the case of membrane separation plants, pretreatment is necessary since $H_2S$ negatively affects performance in the medium term. The multistage membrane strategy is typically adopted to recover $CH_4$ up to 99.5%. Cost and reliability are the main factors limiting MEB's market penetration today (Prussi et al., 2019).

The organic solvent absorption techniques are based on the gases' solubility in the biogas, in an organic solvent (e.g., methanol, N-methyl pyrrolidone, and polyethylene glycol-ethers) are used to absorb $CO_2$ in the plants of physical absorption. In contrast, amine wash is widely used for chemical absorption (Prussi et al., 2019).

Cryogenic separation is a well-established gas separation technology for various large-scale industrial applications. The physical principle behind the cryogenic technique is that gases such as $CO_2$ and $H_2S$ liquefy under different pressure and temperature conditions: Cryogenic plants operate at very low temperatures (−170 °C) and high pressure (80 bar). Biogas purification can be done using cryogenic technology, obtaining the lowest methane losses, but current reduction factors increase specific costs. Despite the higher costs, the cryogenic process continues to be of interest to produce highway fuel since it allows the production of liquefied natural gas (Bio-LNG) (Prussi et al., 2019).

Biological methods represent an interesting alternative to current biogas improvement techniques. One of them is the biological separation by hydrogenotrophic methanogenesis, which consists of hydrogenotrophic methanogens to convert $CO_2$ and $H_2$ into $CH_4$. Despite the potential advantages of these techniques, current technical challenges limit market deployment and current practical interest for the sector, as they entail the need for a two-stage process and can only be applied in locations with a continuous surplus of renewable electricity.

Another method for the biological improvement of biogas is the improvement of the biogas through processes of algae and bacteria. This technology has become a cost-effective and environmentally friendly platform that removes $CO_2$ and $H_2S$ in a one-step process. The improvement of photosynthetic biogas is based on the associated fixation of $CO_2$ by microalgae using solar energy and the oxidation of $H_2S$ to $S^0/SO_4^{2-}$ by sulfur-oxidizing bacteria using photosynthetically produced oxygen (Prussi et al., 2019; Rodero et al., 2019).

## *2.4 Biobutanol*

Biobutanol is alcohol composed of a 4-carbon structure with the formula $C_4H_{10}O$. By fermenting acetone–butanol–ethanol (ABE) from carbohydrates such as starch and glucose using a bacterium called *Clostridium acetobutylicum*, biobutanol is obtained (Karthick & Nanthagopal, 2021). To produce biobutanol, different sources of biodegradable biomass with high starch content such as wheat, corn, rice, biomass from sugarcane can be used. Therefore, feedstocks used for the production of this biofuel come into conflict with feed and food supply. In this scenario, there is a trend towards using agricultural, forestry, and urban residues to produce biobutanol.

If residual biomass is used as a substrate, it would be an alternative solution for the shortage of fossil fuels, resulting in a reduction in damage to the environment (Karthick & Nanthagopal, 2021). Greenhouse gas emissions are greatly reduced by using biobutanol for vehicle use. It can be added to a mixture of gasoline in any proportion up to 100% and in diesel up to 30% by volume without modifying the gasoline or diesel engine (Karthick & Nanthagopal, 2021). Biobutanol is chemically like butanol obtained from petroleum. Compared to ethanol, butanol has 30% more energy content as it comprises a longer hydrocarbon chain. It has properties closer to those of gasoline. It is estimated that biobutanol could mitigate $CO_2$ emissions of around 400.000 tons of $CO_2$ eq. (Szulczyk & Cheema, 2021).

According to (Karthick & Nanthagopal, 2021), from a total mass of hydrolyzed residue of 57.27 kg, 12.2 kg of butanol, 5.7 kg of acetone, 1.5 kg of ethanol, 0.9 and 1 kg of butyric acid are obtained. According to these studies, the composition of the fermentation results depends on the substrate and the pretreatment applied. A butanol concentration of 30.86 g/l and a total ABE of 47.20 g/l were obtained from the hydrolyzed residue of barley straw. A butanol concentration of 7.40 and 11.70 g/l of total ABE was obtained for the corn stubble hydrolyzate. For the hydrolyzate of rice straw, 5.10 g/l of butanol and 8.10 g/l of total ABE are obtained. They result in a concentration between 60–65% of butanol per total ABE. Butanol derived from municipal solid waste can help reduce greenhouse gases by more than 100% compared to gasoline. Some authors claim that in addition to the use of waste sources for $CO_2$, drastic improvements in biobutanol generation technology are needed to increase cellular productivity and replace fossil fuels. The need for friendly integrative approaches between government, research organizations, and industries is necessary to effectively implement fermentation and extraction techniques.

## 3 Case Study

The world's staple crops are cereals, rice, and corn. All of them generate for this use a lignocellulosic residue that can be used in traditional applications: livestock bedding and gardening mulch. However, production normally exceeds the demand, and large amounts of these materials remain unused. Recently, energetic utilization has been proposed with the generation of pellets and briquettes (Choudhury et al., 2021). However, this promising application is limited to thermal energy production. In this study, three alternatives are proposed for the use of this by-product for the generation of biofuels applied into the transport sector. The net energy production in biofuel is calculated considering 1 $m^3$ of cereal straw substrate, rice, and corn. These substrates are evaluated as feedstock for biomethane production through anaerobic digestion and fermentation to produce bioethanol or biobutanol. GHG emissions involved by the unit of energy generated (kWh) or distance (km) traveled in the case of each substrate and type of biofuel are presented.

World production of staple crops is increasing significantly. Cereal production is around 2800 million tons, according to data from the latest FAO report. Wheat production is close to 800 million tons. As for rice, current production is above 500 million tons. The world production of corn is the most abundant, and this is around 1200 million tons. The USA is the most important producer of this crop. More than 50% of the world's corn is produced in the USA. The amount of residue (stubble) generated during the use of a crop can vary depending on the climate, type of soil, the management of the crop, the variety used, and the crop yield. The amount of residue produced can be calculated based on your Harvest index (HI). This index is obtained from the relationship between the grain's weight and the plant's total weight at maturity without considering the roots. This index can vary according to the surface, variety, and management of the crop. The following relationship was used for the calculation:

$$\text{Harvest index (HI)} = \frac{\text{Grain weight (GW)}}{\text{Total plant weight except roots}} \tag{1}$$

$$\text{Straw production } (t/\text{Ha}) = \text{Grain production}(t/\text{Ha}) \cdot \frac{(1 - \text{HI})}{\text{HI}} \tag{2}$$

Figure 1 shows the increasing trend in stubble production worldwide. Due to the low solubility in water and very resistance due to the decomposition of lignocellulosic materials, a hydrolysis process must be included in order to transform these materials into biofuels. Through hydrolysis, greater acceleration in the decomposition of lignocellulose and cellulose into sugars is achieved, and the accessibility of these sugars for subsequent processing is improved. Chemical methods will require a large amount of water and reagents (strong acids or bases), as well as high-temperature conditions. However, biological methods do not require reagents or large amounts of water and can be carried out at or slightly higher than ambient temperatures. The enzymatic hydrolysis processes are biological methods widely used at an industrial level (Beig et al., 2021). Pretreatment allows cellulose hydrolysis yields to increase from less than 20% of theoretical yields to values greater than 90% and will be essential for better energy use. (Haldar & Purkait, 2021; Naik et al., 2021).

Many techniques are used for pretreatment. The choice of technologies will depend mainly on the type of substrate, age, and the growing environment. The most common treatments are thermal, chemical, physical/mechanical, ultrasonic, microwave, biological, and metal addition methods (Haldar & Purkait, 2021), (Naik et al., 2021). The main categories of raw material pretreatment are as follows (Table 1):

The main processes for obtaining biofuels from stubble materials are shown by means of graphs, corresponding to bioethanol, biobuthanol, and biomethane production (Figs. 2, 3, and 4).

Four phases are proposed to evaluate GHG emissions involved in each biofuel production process (see Fig. 5). The first phase consists of calculating the potential of each substrate, taking into account the chemical composition and physical features as well as the transformations required.

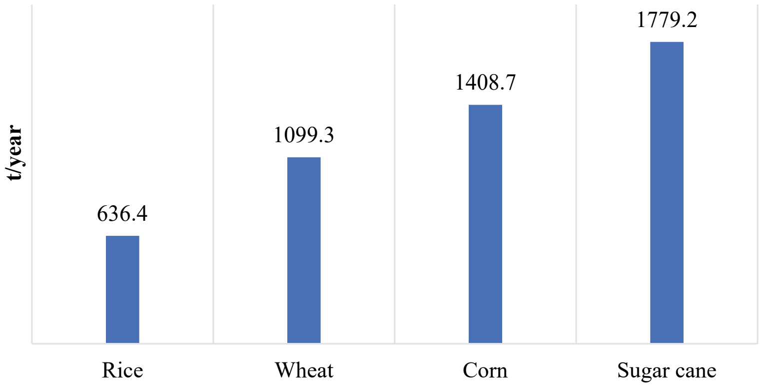


**Fig. 1** Global stubble production

**Table 1** Classification into pretreatment categories applied to stubble

| Pretreatment | Technologies |
|---|---|
| Physical | Mechanical extrusion grinding microwave irradiation ultrasound |
| Chemical | Diluted acid mild alkaline ozonolysis ionic liquids |
| Physicochemical | Vapor explosion compressed hot water hydrogen peroxide soaked in ammonia Electrohydrolysis |
| Biochemical | Mushroom enzymatic |

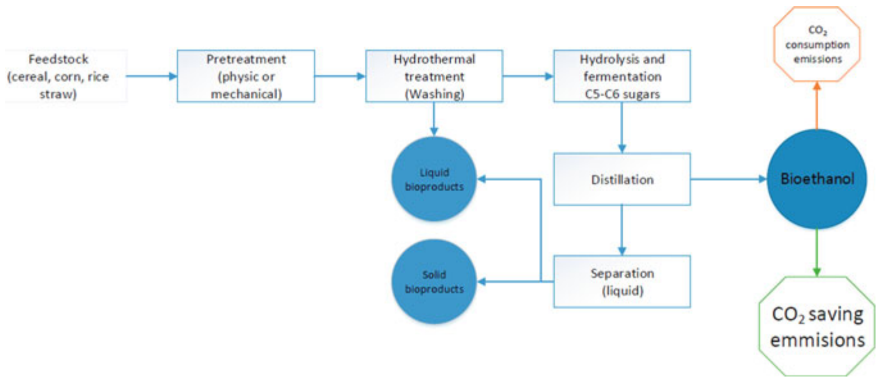


**Fig. 2** Bioethanol process flow diagram

The second and third phases consist of the estimations of energy output and input, respectively. According to previous studies, energy consumption was estimated based on Energy Return on Investment (EROI) determination. Following Hall et al. (2011), the EROI analysis is sensitive to the guidelines chosen in the study. In the present work, lignocellulosic substrates have been considered a secondary by-product within

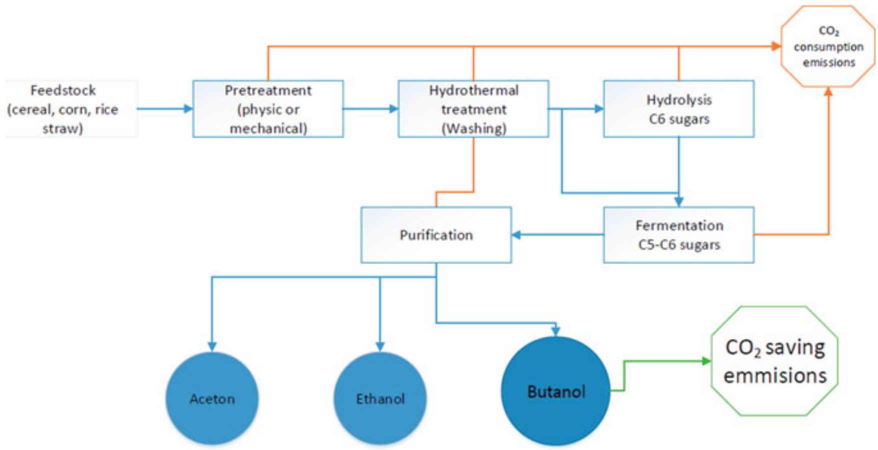


**Fig. 3** Biobutanol process flow diagram

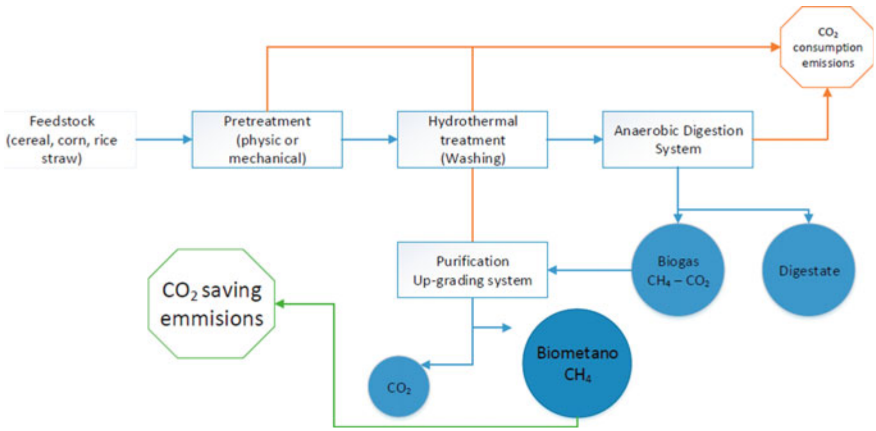


**Fig. 4** Biomethane process flow diagram

the main agricultural activity, and therefore, the consumption in grain production has been considered zero following the criteria reported by Kim and Dale (2005). The following stoichiometric equations have been taken into account:

Hemicellulose is transformed into xylose, glucose, and other sugars after pretreatment:

$$\text{Hemicellulose} \rightarrow (C_5H_{10}O_5) + (C_6H_{12}O_6) + \text{ other sugars} \quad (3)$$

Cellulose after the hydrolytic action of endoglucanases,ellobiohydrolases, and glucosidases is transformed into glucose

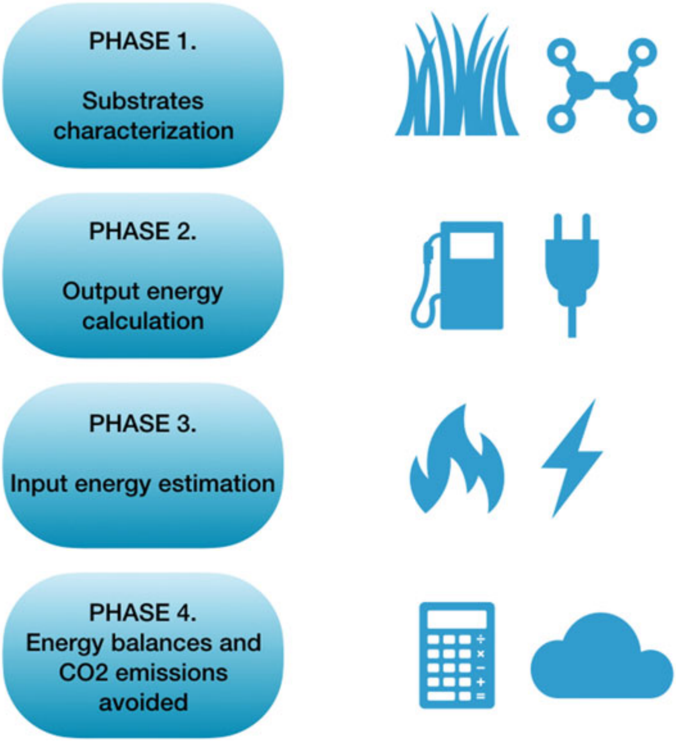


**Fig. 5** Methodology proposed

$$(C_6H_{10}O_5)2n \rightarrow n(C_{12}H_{22}O_{11}) \rightarrow 2n(C_6H_{12}O_6) \quad (4)$$

These products will be the precursors of ethanol after fermentation and distillation:

$$3(C_5H_{10}O_5) \rightarrow 5(C_2H_5OH) + 5CO_2 \quad (5)$$

$$(C_6H_{12}O_6) \rightarrow 2(C_2H_5OH) + 2CO_2 \quad (6)$$

In the case of ABE fermentation, there will have the following transformations:

$$(C_6H_{12}O_6) \rightarrow (CH_3COCH_3)(\text{Acetone}) + 3CO_2 + 4H_2 \quad (7)$$

$$(C_6H_{12}O_6) \rightarrow (C_4H_9OH)(\text{Butanol}) + 2CO_2 + H_2O \quad (8)$$

$$(C_6H_{12}O_6) \rightarrow 2(C_2H_5OH)(\text{Ethanol}) + 2CO_2 \quad (9)$$

For biomethane obtention, there are reactions different because the process is based on anaerobic digestion. We have the following transformations:

$$(C_6H_{12}O_6)\ n \rightarrow 3n(CH_4)\ (\text{biomethane}) + 3n\ (CO_2) \tag{10}$$

In the third phase, energy production is calculated for each case, then the estimated consumption of phase 2 is subtracted from the energy potential calculated in phase 1. The fourth phase corresponds to the energy balances, and estimation of $CO_2$ avoided during the process. Following this approach, the global emissions of $CO_2$ equivalent that can be avoided in the case of generating energy or biofuel of lignocellulosic origin are calculated compared to the use of traditional fossil fuels, taking as a reference the data presented by (Helmers et al., 2019). At this point, it must be considered the possible economic revenues derived from $CO_2$ savings. Taking the $CO_2$ per ton stock market as a reference, it can be seen how there has been a very notable upward trend in recent months, finding the price of $CO_2$ around \$40 per ton in January 2021 and around \$70 the late summer of the same year. (Fig. 6). However, this estimation has not been included in this work since the economic incentives differ vary considerably between countries and geographical areas. In this sense, a section devoted to biofuels normative is included (see Sect. 4).

The physical and chemical parameters of each substrate considered are quite similar, although it is true that small variances in terms of density or composition will impact the final biofuel output. Average values have been taken for each case since these parameters are also highly dependent on environmental factors (humidity, temperature, light, etc.). Table 2 presents the data obtained, where it can be seen that the density of wheat straw is 0.17 kg/l per 0.15 and 0.13 of rice straw and corn stubble. Regarding the cellulose content per $m^3$ of the substrate, wheat straw has 60.16 kg while rice is 51.52 kg and corn is 43.82 kg. For hemicellulose, corn stubble

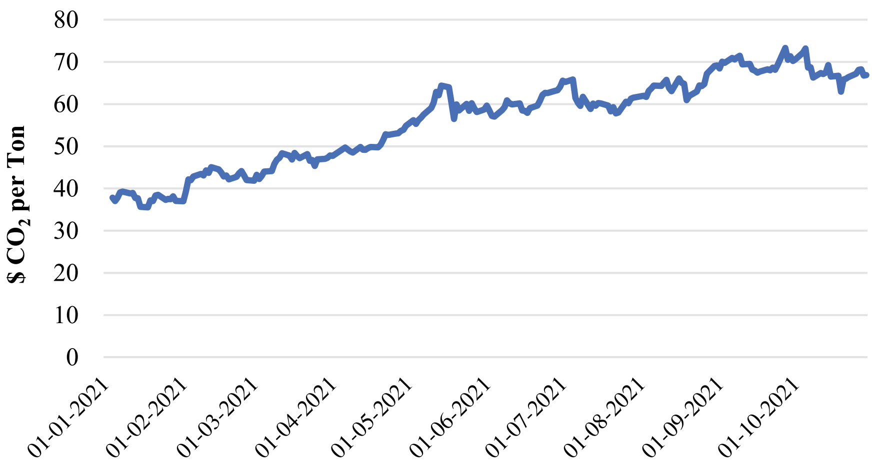


**Fig. 6** Price of $CO_2$ in 2021. *Source* SENDECO$_2$ (European $CO_2$ trading system)

**Table 2** Physical parameters of the proposed substrates (cereal straw, rice straw, and corn stubble)

| | Cereal straw | | Rice straw | | Corn straw | |
|---|---|---|---|---|---|---|
| Volume ($m^3$) | 1.00 | $m^3$ | 1.00 | $m^3$ | 1.00 | $m^3$ |
| Straw density | 0.17 | kg/l | 0.15 | kg/l | 0.13 | kg/l |
| Flow (kg) | 160.00 | kg | 160.00 | kg | 160.00 | kg |
| Medium humidity | 0.94 | % | 0.92 | % | 0.82 | % |
| Cellulose content | 60.16 | kg | 51.52 | kg | 43.8208 | kg |
| Hemicellulose content | 45.12 | kg | 39.744 | kg | 45.264 | kg |
| Lignin content | 31.584 | kg | 33.12 | kg | 6.9536 | kg |

has 45.26 kg, rice straw 39.74 kg, and wheat straw 45.12 kg. (Emami et al., 2014; Ishii & Furuichi, 2014; Saad, 2012; Viamajala et al., 2007; Zhang et al., 2013).

The study was divided into two parts corresponding to net energy production and energy produced as biofuel regarding GHG emission savings. GHG savings were calculated in terms of $CO_2$ equivalent. Net energy production is displayed in Fig. 7. The process of obtaining bioethanol presents a considerably better performance reaching 66.11 kg of $CO_2$ equivalent when wheat straw was used as substrate. Biomethane showed higher GHG savings when corn stubble is used as a substrate, reaching 35.74 kg of $CO_2$, significantly higher than the value obtained for rice straw, 19.52 kg of $CO_2$. This is due to the greater efficiency in biodegradability of these materials under anaerobic digestion. Biobutanol obtained delivers the best result when the rice straw is utilized, reaching a saving of 13.89 kg of $CO_2$ equivalent. This value is low compared to the other processes because only the generated butanol has been taken into account in the ABE fermentation, neglecting the energy embodied in the other by-products: acetone and ethanol.

Regarding the $CO_2$ emissions avoided using the energy obtained in biofuel (see Fig. 8), a very similar trend was observed. Savings of 55.25 kg of $CO_2$ equivalent were reached in the case of bioethanol production with cereal straw and 50.81 kg in the case of rice straw. Biomethane production as biofuel resulted in 36.06 kg of $CO_2$ being avoided. Butanol based on corn stubble showed a value of 13.89 kg of $CO_2$, and a similar value was found when rice straw was considered.

$CO_2$ emissions can be greatly reduced by replacing fossil fuels with biofuels produced from agricultural residues. Bioethanol presented the highest $CO_2$ savings. This fact is directly related to the considerably lower energy consumption in the production process of biofuel from lignocellulosic waste compared to the production of biomethane and biobutanol.

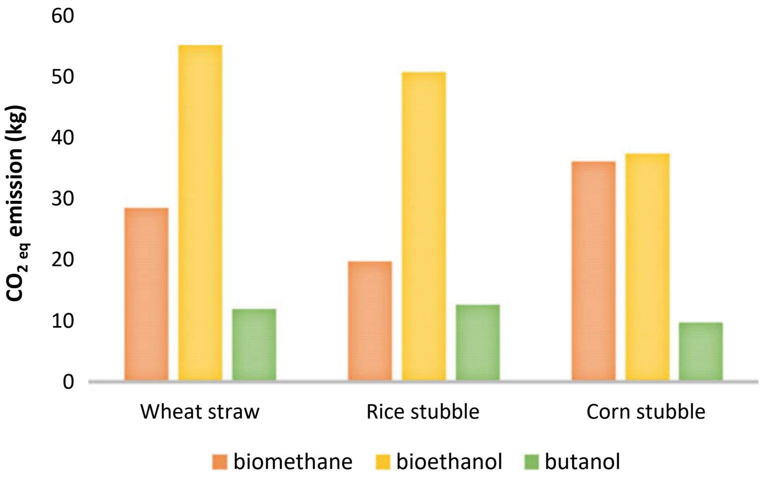


**Fig. 7** $CO_2$ emissions avoided in the net energy generation starting from 1 $m^3$ of substrate for cereal, for rice and corn stubble

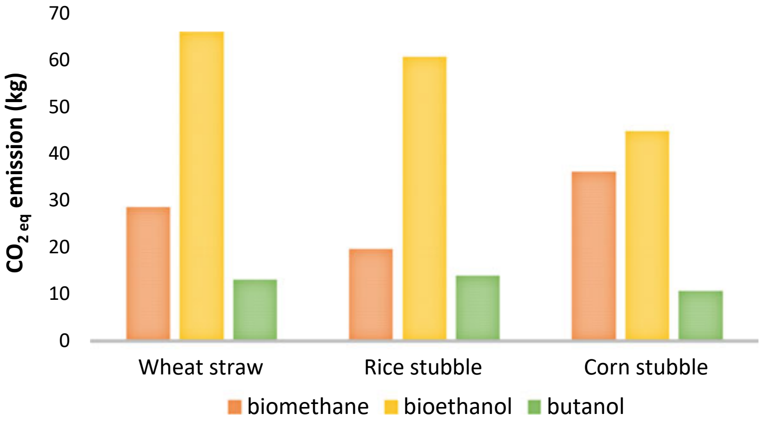


**Fig. 8** $CO_2$ emissions avoided in biofuels production starting from 1 $m^3$ of substrate for cereal, for rice and corn stubble

## 4 Biofuels Normative in Low Emission Economies—The European Initiative

### *4.1 Approach*

In a context where the integration between climate and energy is unquestionable, biomass energy plays a fundamental role in the energy transition towards a renewable model in order to achieve, at the same time, a decarbonized and circular economy. Apart from a great diversity of programmatic and normative instruments that have followed one another as a result of the Paris Agreement until reaching the European Green Deal, the guide that marks the future of environmental policies is the Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action. This Regulation is a common legislative basis whose cornerstone is the integrated national energy and climate plans that have already been approved by the Member States and reviewed by the European Commission.

Through this section and a brief synthesis, we intend to investigate how bioenergy and biomass fuels have been considered in the new Renewable Energy Directive—objectives and barriers—and their role in the circular economy.

### *4.2 A Common Regulatory Framework for Renewable Energy from Biomass*

The Treaty on the Functioning of the European Union (TFEU) includes, between its objectives, the promotion of renewable energy. Therefore, the Directive (EU) 2018/2001 of the European Parliament and the Council—related to the promotion of the use of energy from renewable sources (DERII)—pursues this objective. At first sight, we cannot affirm that it is a new normative instrument: although it presents novel aspects, it is a recast version that gathers the various modifications introduced in Directive 2009/28/EC (of April 23, 2009). This Directive is related to promoting the use of energy from renewable sources (DERI) throughout its validity period.

Although it establishes a common framework for promoting renewable sources, it does not determine specific regulations for each type of renewable energy—neither is its mission nor addresses multiple details. Instead, it sets quantitative objectives accompanied by a series of measures for its achievement. We should ask whether this common framework clarifies the treatment of bioenergy in such a way as to facilitate the drawing up of the legal frameworks of the respective Member States when transposing it.

> "It is an intermediate step, a transition towards long-term objectives, towards climate neutrality expected for 2050, but which raises notable and complex challenges" (Valencia Martín, 2020), within a context where the integration between climate and energy is already an unquestionable reality. It is a clear commitment to diversifying the energy model through

an innovative principle such as “clean energy generation,” without forgetting “technological neutrality.”

Now, if an energy source has deserved special attention through the Regulation of specific aspects, it is precisely bioenergy, that is, energy from biomass. It is renewable energy which continues to be the main source of the Union at a general level. As can be seen from the latest report on renewable energy [COM (2020) 952 final]: With a share of around 60% in 2018, it represents 10.3% of total energy consumption and an emission savings of 310 $MtCO_2$, equivalent to around 7% of greenhouse gases (GHG) emissions for that year.

It is also worth mentioning that bioenergy is the only renewable source encompassing the electricity, heating and cooling, and transport sectors, so its consolidation is essential.

There are plenty and diverse definitions of biomass, which makes its legal treatment extremely difficult to the point of being able to affirm “each biomass is a world.” The DERII itself defines it as “the biodegradable fraction of products, residues, and wastes of biological origin from agricultural activities, including substances of plant and animal origin, forestry and related industries, including fishing and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin.”

As the definition proposed in the DERI, the intermixing of “products,” “waste,” and “waste” continues with the problems that it entails. Nevertheless, this new Directive includes the “biodegradable fraction” of any waste, unlike the DERI, which only considered industrial and municipal waste. Despite this characteristic note, biomass regulation will not be homogeneous precisely because of the fine line between “residue,” “product,” and let alone, “waste”. It is important to mention that, for the first time, waste is defined in this DERII as that “substance that is not the final product intended to be obtained directly in a production process; it is not a primary objective of the production process, and the process has not been deliberately modified to produce it.”

Although it does not have a large contribution in terms of novelty, the definitions of “agricultural biomass,” “forest biomass,” “biomass fuel” are introduced, which are those gaseous or solid fuels produced from biomass and “biomass fuel with low risk of indirect land-use change.”

The DERII establishes a binding global target for the European Union of at least 32% renewable energy in gross final energy consumption by 2030. Unlike the DERI, which sets mandatory and specific national targets for each of the Member States, in DERII, the Member States must contribute to the fulfillment of the global objective by setting specific objectives in their respective integrated national energy and climate plans. For this, they have necessarily started from the percentage of renewable energy quota set for 2020. Otherwise, it would represent a clear setback. Nevertheless, they are free to set a more ambitious starting point. In this context, the Commission must make sure that the common objective is achieved by the objectives set by each Member State.

Two aspects related to bioenergy addressed in the DERII are worth highlighting and will be analyzed below.

1. Sustainability criteria and emission reduction

Sustainability criteria and emission reduction should be carefully considered for biofuels, bioliquids, and biomass fuels. This is not a new aspect of the DERII because they were already contemplated in the DERI, although only for agricultural biomass, waste and biofuels, and liquid biofuels (for obtaining heat and electricity).

Availability and sustainability of the resource must play in unison when it comes to the use of biomass, considering that the demand for agricultural, forestry, or other raw materials requires the adoption of a series of measures to ensure the correct use of the soil and prevent the destruction of areas rich in biodiversity.

Through the Joint Research Center (JRC), the Commission is assessing the supply and demand of biomass at the global and EU level and its sustainability. The Center is mandated to provide data, models, and analysis on biomass supply and demand with short- (2030), medium- (2050), and long (2070)-term perspectives (European Council, 2021).

They are an acceptable energy alternative that does not compromise food safety and does not harm the environment. Hence, the DERII has defined those that are considered biomass fuels with a low risk of indirect change in land use, which occupy a preferential position (Article 2, definitions, Paragraph 32). They are not subject to a specific and decreasing limit in calculating the total share of renewable energy nor in the share of renewable energy in the transport sector. On the contrary, it is only required for those fuels "produced from products intended for human and animal nutrition, for which a significant expansion of the production surface with high carbon reserves has been observed." It is not easy to determine when the expansion of the raw material is "significant" and measure the emissions derived from indirect changes in land use, which will depend on multiple factors.

Nevertheless, Europe is committed to the use of biofuels for the transport sector. One of the three addends to calculate the final gross consumption of energy from renewable sources in each Member State is precisely the final consumption of energy from renewable sources in the transport sector (Article 7 DERII)*.

The content of the DERII deduces a certain predilection for residual biomass connected with the inherent value of the circular economy and the waste hierarchy in order to avoid unnecessary distortions in the raw material markets and to reduce to the maximum the consequences derived from direct and indirect changes in land use, or additional demands on land. There is also the inclination towards advanced biofuels, which are obtained from biomass that does not compete with the food sector. The "EU Strategy confirms this approach on Biodiversity by 2030. Reintegrating nature into our lives," which advocates for production of bioenergy that minimizes the use of whole trees, crops, food, and animal feed.

On the other hand, the sustainability of fuels produced from biomass is questionable due to the additional emissions, hence the importance of considering where and how biomass is produced and extracted.

Sustainability and emission reduction are mandatory conditions, which shows the high level of control planned over bioenergy in the DERII aiming to replace fossil fuels with renewable fuels. It should be noted that compliance with the so-called sustainability and GHG savings criteria must be demonstrated through certification regimes, the so-called voluntary regimes recognized by the Commission, which will carry out a thorough evaluation to ensure their reliability, transparency, and independent audit.

It is a question of proving that the producers meet the sustainability criteria and that it is possible to track it until the origin of the raw material. In this line, Article 30 of the DERII provides norms to verify the bioenergy sustainability criteria, including greater supervision at national and Union levels, of the voluntary regimes and third-party audits. It is about improving the traceability of renewable fuel through a database of the Union, without prejudice to the use of the creation of national databases.

2. Biomass fuels and their contribution to the renewable energy share

Another point of interest is how to compute the share of renewable energy from biofuels, bioliquids, and biomass fuels, which is not automatic. The DERII requires, in general, that only if the sustainability and emissions reduction criteria provided for in Paragraphs 2–7 and 10 of Article 29 are met, their energy will have the following purposes:

(1) To contribute to the global objective of the EU in terms of renewable energies: of at least 32%, as proposed for each of the Member States and, in the case of Spain, 42%; (2) to assess compliance with renewable energy obligations, in particular, the obligation established for fuel suppliers in order to ensure that the share of renewable energy in the transport sector is, at least, 14% in 2030 later than; and (3) to be entitled to financial aid for the consumption of biofuels, bioliquids, and biomass fuels.

Anyway, biomass fuels must meet both requirements when used in facilities that produce electricity, heating, and cooling or fuels, with a total nominal thermal power equal to or greater than 20 MW in the case of solid fuels derived from biomass; and with a total nominal thermal power equal to or greater than 2 MW in the case of gaseous fuels derived from biomass. However, Member States may apply these criteria to installations with a lower total rated thermal power.

Biofuels derived from residues and wastes of agricultural lands will only be considered for renewable energy quota contribution purposes when operators or national authorities have implemented monitoring or management plans to address the negative impacts on the soil quality and soil carbon.

Those produced from agricultural biomass cannot be made from raw materials from lands of high biodiversity value or with high carbon stocks, that is, lands in January 2008 (or later) were framed in the categories established in Paragraphs 3 and 4 of Article 29.

Regarding the biofuels produced from forest biomass, they must comply with a series of criteria to minimize the risk of using forest biomass derived from unsustainable production. A recent report published by the Commission highlights that compliance with the DERII criteria for sustainable management depends, firstly, on the existence and effective application of national forest legislation and, in its absence, on the existence of forest management systems in the biomass supply area (Camila, 2021).

Finally, the reduction of GHG emissions related to the use of those three biofuels range from 50 to 70% as a minimum, depending on for how long the companies are or will come into operation, and it will be calculated according to Paragraph 1, Article 31 of DERII.

Despite the short period of existence of the DERII and its derogation having been postponed until July 1, 2021, parallel to the date on which the Member States had to transpose it into their legal systems, which ended on June 30, 2021; The truth is that through the well-known European Green Pact [COM (2019) 640 final], a modification was announced, following the commitment made by the EU to achieve climate neutrality by 2050.

In fact, in December 2020, the European Council endorsed a new binding target for the EU aiming at a net internal reduction of GHG emissions, by 2030, of at least 55% compared to 1990 values. Doing this outperforms the goal established in 2014 to reduce emissions by at least 40% by 2030 (European Commission, 2021). The Commission has proposed increasing this target to "at least 55%" in its amended proposal for the European Climate Law [COM (2020) 563 final]. The members of the European Parliament have a straightened proposal: a reduction of 60% by 2030 since the increase in national objectives also seeks profitability and equity. Finally, the binding objective that will be transferred to the definitive Regulation and that will be of direct application in the Member States is the reduction of emissions by "at least 55%."

As specified in the assessment impact of the Climate Objective Plan to reduce GHGs by 55%, at the same time, it will be necessary to reach a share of renewable energies by 2030 of between 38 and 40% [COM (2020) 562 final]. The main underlying idea is that the reduction of emissions depends on the expansion of renewable energies, which, as reflected in the Strategy for the Integration of the Energy System [COM (2020) 299 final], must be distributed geographically and flexibly integrate different energy vectors, while continuing to make efficient use of resources and avoiding pollution.

*Regarding the transport sector, DERII targets a minimum share of renewable energy of 14% in 2030, with a contribution of advanced biofuels and biogas produced from raw materials listed in Annex IX, Part A, at least 0.2% in 2022, 1% in 2025, and 3.5% in 2030 (Articles 25, 26, and 27 DERII). Besides, it predicts that the proportion of biofuels consumed in transport, when produced from food and feed crops, will not be more than one percentage point higher than the quota of fuels on the final energy consumption in the railway and roadway modes in 2020 in the Member State, with a maximum of 7% of final energy consumption in the transport sectors by rail or roadway.

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# Role of Biofuels in Building Circular Bioeconomy

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## 1 Introduction

Transportation relies almost exclusively on fossil fuels, particularly petroleum-based fuels like diesel, compressed natural gas, gasoline and liquefied petroleum. As the available amount of petroleum shrinks, the necessity for alternate liquid fuels manufacturing technologies grows in the hopes of extending the liquid fuels culture while reducing the effects of the approaching transportation fuel shortfall. Biofuels should be investigated as a viable technology by both developing and developed countries for various reasons. Concerns regarding energy security, environmental difficulties, foreign exchange savings, and socio-economic challenges confront rural areas in all countries. Biofuels have recently gained popularity due to their environmental benefits (Balat, 2009; Demirbas & Dincer, 2008). Biofuels provide several advantages over traditional fuels, including greater energy security, less environmental effect, foreign exchange savings, and reduced rural socio-economic concerns. Biofuel technology can assist both poor and developed countries.

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For the reasons stated above, biofuels are likely to increase quickly in the vehicle fuel market during the next decade. Biofuels can provide all countries with a source of peaceful energy. They are natural resources that may be found worldwide and are renewable. The economic ramifications of the biofuel transition will require more attention from policymakers. The idea of interconnection and balance between economic, social, and environmental concerns is embodied by the concept of sustainable development (Demirbas, 2009). Biofuel is a type of renewable energy that can substitute petroleum-based fuels. It's made with substances that are found in nature (biobased). The most prevalent biofuels, such as ethanol created from maize, wheat, or sugar beet, and biodiesel made from oilseeds, are made from typical food crops that thrive in fertile soil.

On the other hand, ethanol is a gasoline substitute/additive that may be generated from various domestic cellulosic biomass resources, including woody plants, herbaceous, agricultural and forestry waste, and a significant portion of municipal and industrial solid waste streams. One method for reducing crude oil usage and pollution is making ethanol from biomass. Biodiesel, a less harmful alternative to petroleum diesel, is also gaining traction (Sigar et al., 2008).

Biofuels are biomass-based solid (biochar), liquid (biodiesel, vegetable oil, and ethanol), and gaseous (biogas and biohydrogen) fuels (Chhetri & Islam, 2008). Liquid biofuels might be a realistic option. Even though liquid biofuels are a viable alternative to petroleum, some still include a small amount of it. The most notable difference between biofuels and petroleum feedstocks is their oxygen content (Demirbas, 2007, 2008). However, the approach has not yet evolved, and scientists and economists are still studying the scientific and economic viability of biofuels in various academic fields (Demirbas, 2008; Demirbas & Dincer, 2008). While studies like this provide a clear picture of the economic and scientific limits of biofuels in aviation, the social and technological factors controlling the environmentally friendly marketing of aviation biofuels are frequently overlooked. Gaining industry consensus on the fuel's environmental and cost-effectiveness is one of the most difficult components of introducing aviation biofuels. The majority of $CO_2$ emission reduction potential occurs during the production stage, when feedstock plants absorb $CO_2$, reducing the amount produced during consumption to some extent. Inedible crops like camelina, halophytes, and algae use various biochemical or thermochemical processes (Rye et al., 2010). Under ideal conditions, biofuels have been demonstrated to lower emissions by up to 85%, as per the study done by Bailis and Baka (2010).

A definitive study of systemic transformation is currently necessary to capture the diverse characteristics of interconnections across the industry, technology, markets, policy, and society. This chapter will study different pathways and restrictions for growing green innovation from a socio-technical approach. Also, we will discuss the effect of biofuels in a circular economy along with its constraints.

## 2 What Are Biofuels, and What Are Their Advantages and Disadvantages?

Currently, fossil fuels are the most common energy source, accounting for about 80% of total energy consumption, with the transportation sector accounting for 58% (Escobar et al., 2009). These oil and fossil fuel reserves are fast decreasing, and they have been identified as significant contributors to dangerous gas emissions. Glacier retreat, biodiversity loss, climate change, sea-level rise, and other negative effects are all caused by these gases. Because of the growing demand for this fossil fuel, crude oil prices have risen, putting a damper on global economic activity. Two significant drivers of unpredictably high fuel demand are industrialization and motorization for high-speed modern globe travel (Agarwal, 2007).

Biofuels are many different types of alternative energy sources now available. Biofuel production utilizing sustainable biomass is a cost-effective alternative to nonrenewable fuels; thus, scientists and researchers continually work on it. Biofuels have several advantages over petroleum-based fuels like (a) extracting it from biomass is simple, (b) because of their biodegradability, they last a long time, (c) $CO_2$-cycle-based biofuel combustion, and (d) being environmentally friendly. Biofuel's automobile market share will expand dramatically over the next decade due to its ecologically friendly features (Fig. 1). In order to expand production and associated byproducts, this will demand a significant expansion of the agriculture industry (Kang et al., 2014).

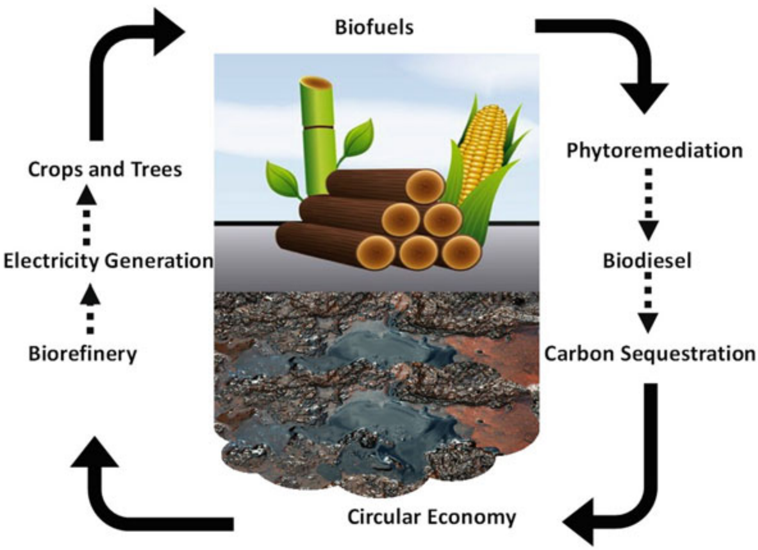


**Fig. 1** Role of biofuels in the sustainable environment and energy

Whether gaseous, solid, or liquid, biofuels are all made primarily from biomass. Based on the chemical and intricate nature of the biomass, biofuels are separated into three generations. The chemical and complicated character of the biomass is used to create the first, second, and third generations. Biodiesel and vegetable oils are examples of first-generation biofuels made from crop plants, whereas bioethanol and biohydrogen are second-generation biofuels made from agricultural byproducts and energy plants that thrive in fertile places (Arthe et al., 2008).

Biomass can also be viewed as a low-cost, renewable source of energy that can be used at any time. India's current annual biomass supply, which includes forest and agricultural biomass, is projected to be around 500 million metric tons, with an energy potential of over 18,000 megawatts. Many tons of biomass derived from marine, agricultural, forest, industrial, and municipal solid waste decompose unpredictably, resulting in hazardous gas emissions that cause environmental issues (Taherzadeh & Karimi, 2007). The potential reuse and recycling of biowaste can also be beneficial, like reduced gas discharges from the greenhouse through green oils, reduced pollution, and improved rural economy (Ragauskas et al., 2006).

## 3 Biofuel-Based Economy Biofuel-Based Economy

Traditional fuels cannot match biofuels' costs in today's era of high oil prices. Since the twenty-first century, the biofuel industry has been rapidly expanding. The hydrocarbon economy was shaped during the previous century, and the same processes are shaping the biofuel industry and its biorefineries. Biofuel's effective contribution to the transportation industry will lead to a major increase soon due to its own merits in terms of environmental friendliness. For various reasons, both developed and developing countries consider biofuels to be a viable technology. The indicative national targets could be met if biofuels are employed to improve public transportation. The key measures were a biofuel obligation and a tax decrease to increase the availability of feedstocks for biofuel production (Demirbas & Dincer, 2008).

Energy generation has been a major driving force in agricultural progress. Energy production is critical to agriculture's economic success. The bulk of people living in rural areas and their agricultural productivity are critical to the economy's development. As a result, implementing development programs for integrated rural communities is crucial. These community programs will compel the country's social and economic progress. The simultaneous synthesis of bioethanol and bioethanol from sugar juice is extremely appealing economically in areas where hydroelectricity is more affordable. Biomass to methanol conversion is more expensive and inefficient than natural gas, biomass, or coal to hydrogen conversion. The depletion of traditional energy sources such as petroleum, natural gas, and coal is frequently mentioned in research papers and assessments, and big biomass is considered the best alternative for meeting energy demand (Bailis & Baka, 2010).

## 4 The Condition of Biorefineries in Different Parts of the World

In both social and economic terms, basic human needs necessitate the use of energy. However, research has demonstrated that burning fossil fuels promote climate change by increasing greenhouse gas emissions. Biomass as a long-term economic development resource: agriculture, fisheries, food manufacturing, paper manufacturing, and biotechnological, chemical, and energy-producing industries all contribute to the biomass economy by converting and producing biowaste, and bioresource streams into value-added products such as feeds, bioproducts, bioenergy, and foods (Hussain et al., 2021a; Younas et al., 2021). On the other hand, the US biomass economy policy mainly focuses on synthetic biology. Food waste, manure, and sewage are waste streams that have a greater biorefining potential and might be used to generate fertilizer with energy extraction (Maxon & Robinson, 2012).

***The worth of biorefineries***: The bioeconomy has wonderful potential to replace old-style energy making and supply biochemical and biomaterial uses on a large scale. The bioeconomy can utilize several bioresources, such as aquatic and terrestrial resources, and biomaterials, such as plants, microbial components, and animals. On the other hand, the biobased economy originated during the pre-industrial era because of financial constraints, which is not a new concept. An organic feedstock is used to produce wood-based resources, fibers (biomass-derived), paper and pulp, sugar, starch, and oil crops, among other things. Corn, wheat, beetroots, sugar cane, surplus food, wood, agricultural waste, marine biomass, and straw are all examples of suitable feedstocks (Bioeconomy, 2012).

Biorefinery processes are typically integrated rather than isolated technologies, making it difficult to determine their precise condition. Bioethanol, biodiesel, biopolymers, bioplastics, biochips, biogas, syngas, bio-oil, and biochar are only a few examples of biomass-based refinery technologies in use today. The feedstocks used by conventional biorefineries, whole crop, oleochemical, lignocellulosic feedstock, green, and aquatic biorefineries are classified. Based on the conversion method, thermochemical and biochemical biomass refining are two biorefineries. Pyrolysis and gasification are thermochemical refining processes that break down biomass into cellulose, hemicellulose, lignin, and extractives using a mixture of pressure and heat in the absence of oxygen (Amen et al., 2020). These intermediates can be turned into a wide range of marketable goods. Hydrolysis, fermentation, and digestion are examples of biochemical refining techniques that use biological and chemical components like bacteria or enzymes to break down biomass into a range of mixtures (Hameed et al., 2021; Hussain et al., 2021b).

## 5 Production of Biofuels

Biofuel production can be classified into three stages: first, second, and third. The first-generation manufacturing method entails the production of biodiesel and ethanol conventionally. Transesterification is used to extract oil from oleaginous plants and convert it to a fuel that can be utilized directly by engines in the manufacturing of biodiesel. Vegetable oils in their natural state may be utilized as a fuel in converted engines. Transesterification is a process that utilizes enzymes or acids, alkali, and ethanol or methanol to produce glycerin and fatty acids as a byproduct (Karimi et al., 2006; Rabelo et al., 2011).

In second-generation biofuel manufacturing systems, cellulose hydrolysis is followed by sugar fermentation. Utilizing biological resources to generate syngas (synthesis gas) via the gasification process might be quite beneficial. A variety of catalytic processes can turn this syngas into liquid biofuels. Anaerobic digestion can create methane and natural gas. Agricultural waste or crops are digested as part of the process (Elshahed, 2010). Production of third-generation biofuels: The current process for producing algae-based biofuels is classed as a third-generation process. Algae can easily produce oil, which can be converted into diesel and a fraction of gasoline. Using genomic and metabolic engineering technologies, the carbon metabolic pathway might be guided toward ethanol production as a product. Both photobioreactors and open raceway ponds can be used to grow algal biomass. The third-generation technique produces less stable ethanol than biofuel produced by other technologies (Gaurav et al., 2017).

## 6 Costs, Pricing, and Economic Consequences of Biofuels

The most frequently imported foreign alternative is palm oil, which soon is imported. The vegetable seed oil is transformed into biodiesel through oil refining and transesterification. Reduce the cost of biodiesel by increasing raw material emissions, developing innovative processes, and finding alternative uses for this byproduct that is now being sold with low value due to overstocking. On the other hand, co-solvents such as tetrahydrofuran can combine alcohol, oil, ester, and glycerol systems into a single phase, thus minimizing processing costs (Demirbas, 2008). Previous economic studies on biodiesel have shown that the cost of capital, plant capacity, process technology, raw material costs, and chemical costs are the most critical economic considerations (Zhang et al., 2003). When it comes to the input costs of biodiesel production, raw materials are the most important economic factor, with 75–80% of the total operating costs. Labor, methanol, and catalysts that must be added to the feed add enormous costs (Haas et al., 2006).

However, these advances have not yet made biodiesel economically viable. The costs of producing biofuels vary depending on the raw material, conversion process, production scale, and geographic location. We use the expected process cost of

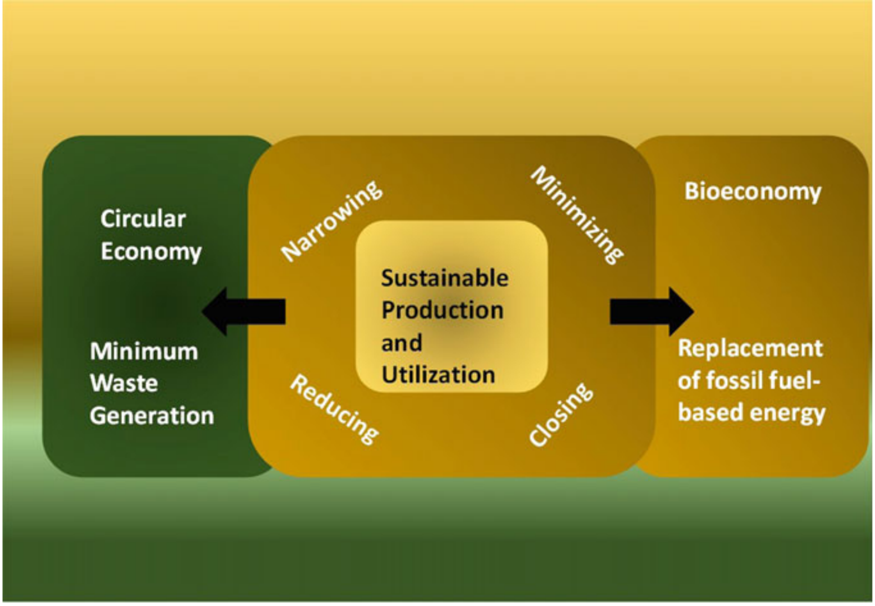


**Fig. 2** Biofuels as a center pyramid for sustainable production and energy utilization

biodiesel production of $0.158/l and the raw material cost of refined soybean oil of $0.539/l and calculate the total cost of soybean-based biodiesel production to be $0.70/l. At all the locations analyzed, ethanol production is currently more energetically expensive than gasoline. Only Brazilian ethanol can compete with gasoline. In the USA, ethanol made from corn is much more expensive than ethanol made from sugar cane in Brazil, while ethanol made from grain and sugar beet is even more expensive in Europe (Fig. 2).

These differences are caused by several factors, including process size, raw material efficiency, capital and labor costs, accounting for byproducts, and the nature of the assumptions. Large-scale production of biobased products has become more and more expensive in industrialized countries. If you ignore the non-market benefits, the cost of manufacturing biofuels can be three times that of petroleum fuels. On the other hand, the production costs for biofuels in developing countries are far below those of the OECD and are very close to the world market price for petroleum fuels (Freire et al., 2002). The raw material costs are an essential economic factor that determines the profitability of biodiesel production. Even so, used cooking oil is 2.5–3.5 times cheaper than native vegetable oil, which can significantly reduce the overall costs of biodiesel production.

The economic benefits of biofuel companies include increasing the value of raw materials, increasing income taxes, investing in factories and equipment, reducing greenhouse gas emissions, reducing reliance on crude oil imports, and helping agriculture by providing additional job and market options for local crops. In recent years, the value of non-food plants has risen sharply. As part of the mandatory reservation plan, growing non-food crops is a strategy for increasing biofuel production. Renewable liquid fuels like ethanol, biodiesel, green diesel, and green gasoline are essential to replace petroleum fuels. Sustainability, greenhouse gas reduction, regional growth, social structure, agriculture, and security of supply are all recognized benefits of renewable liquid fuels (Nhamo, 2009).

Using renewable resources instead of traditional production technologies to generate electricity has a huge socio-economic impact on the local economy—inequality in employment, income, and total output directly and indirectly. The construction of new power plants will bring new employment opportunities, increased production, and more income to the local and regional economies. The purchase and use of local products and services and the direct labor involved in building and operating power plants all contribute to the growth of these categories. The reduction in fuel consumption results from lower prices for renewable liquid fuel and the conservation of resources. In addition to economic benefits, the expansion of renewable energies also benefits the environment, human health, and public safety (EPA, 2002).

The cost and price of ethanol production depend on the plant species, agricultural technology, land and labor costs, plant size, processing technology, and local government regulations. The current cost of making ethanol in a dry mill is $1.65 per gallon. Corn makes up 66% of the operating costs, followed by energy for the operation of boilers and dry DDG (electricity and natural gas) with 20% (Urbanchuk & Director, 2006). In the IEA countries, sugar cane ethanol production costs are generally lower than grain or beet ethanol, which is why sugar cane is mainly grown in developing countries. Therefore, in Brazil and India, where large quantities of sugar cane are grown, sugarcane-based ethanol is becoming a cheaper alternative to petroleum fuels. Although feed and tree raw materials are generally cheaper than cereal and sugar crops, ethanol, made by enzymatic hydrolysis of cellulosic raw materials, requires more processing than ethanol made from starch or sugar-based raw materials. If the conversion costs can be effectively reduced, the cost of producing cellulosic ethanol in OECD countries could be lower than that of grain ethanol. It is estimated that the economic value of ethanol in the EU is $70 per barrel and $50–60 per barrel in the USA. Brazil's price barrier is significantly lower, between 25 and 30 US dollars per barrel (Dufey, 2006).

Even though it can be mixed with gasoline, anhydrous ethanol is more expensive than gasoline. Prices in India have decreased to the point where they are now comparable to gasoline. The US larger conversion plants produce biofuels, particularly ethanol, lower than those in Europe. Warm-weather countries have lower ethanol production costs, with Brazil likely being the lowest-cost producer on the planet. Brazil's sugar cane production costs are currently less than half in Europe. Sugar cane ethanol production in developing countries can be a low-cost source of significant oil substitution globally over the next two decades. The cost of agricultural feedstock accounts for a sizable portion of the total cost of biofuels. The cost of producing biodiesel from oilseeds is influenced by the oil price and competition from high-value applications such as cooking. The most expensive component of the ethanol production process is the plant feedstock. Feedstock pricing, co-product credit, chemicals, labor, maintenance, insurance, and taxes contribute around a third of the overall cost per liter, with energy being a key (and very variable) component. Capital cost recovery accounts for approximately a sixth of the overall cost per liter recovered. Costs have been proven to be significantly affected by the size of a facility. (Tzirakis et al., 2007). Vegetable oil biodiesel and waste grease biodiesel are expected to cost between $0.54 and $0.62/l, while waste grease biodiesel costs between $0.34 and $0.42/l. Biodiesel is not economically viable at the moment, with pretax diesel prices in the USA at $0.18/l and in several European countries at $0.20–$0.24/l, and additional research and technical development will be required (Tzirakis et al., 2007).

### *6.1 The Role of Biofuels in the Development of a Circular Bioeconomy*

The "circular economy" is gaining traction as a means of integrating the entire process for a more cost-effective approach. Resources are generated, utilized, and disposed of in a linear economy, whereas materials are exploited throughout their shelf life to maximize profit in a circular economy.

Additionally, the circular economy plan focuses on material and resource recovery and regeneration after each product's life cycle (Chandel et al., 2020). The value-adding lignin is intended to integrate the entire process into the circular bioeconomy. Pyrolysis, oxidation, and incineration are widely used to convert raw materials into intermediate products and valuable end products. While the application of biofuels has expanded to drug manufacturing, biopolymers, the development of biosensors for glucose detection, and biocomposites, biosorbents, nanocomposites, hydrogels, and other materials, the biofuel cycle-based economy is a conceivable concept (Chandel et al., 2020).

## 7 Barriers to Biofuel Production

The following are the primary constraints and limitations that are preventing this amazing technology from becoming a reality:

## 7.1 The Price of Enzymes and the Availability of Enzymes

To decrease the cost of biofuel manufacturing, effective hydrolytic enzyme synthesis must be developed. Due to the high rate of commercial enzymes, large-scale fuel synthesis is not commercially viable.

## 7.2 Production Units and Facilities

Nuclear and fossil fuels are rapidly declining, resources are scarce and concentrated in a few places, and widespread renewable resources. The energy obtained from renewable resources far exceeds current global energy consumption. The long-term sustainability of the current energy system is a major challenge for economic, fair, and ecological reasons. Various sustainability initiatives and biofuel projects are being implemented to conserve land, communities, and animals. NGOs, government agencies, and business enterprises have participated in these efforts. The combination of public and private investment is essential to accelerate the commercialization of biofuels. For example, Brazil and the Netherlands have signed an agreement to develop biofuel production to support the long-term growth of biofuels made from plants. The USA provides government subsidies to support the research and development of biofuels. China is the third-largest energy producer globally after Brazil and the USA. Large-scale ethanol production is the main concern of the Chinese government (Ghosh et al., 2011).

## 7.3 Fermentation

According to reports, thanks to genetic engineering and improved screening methods, bacteria and yeast will digest both glucose and xylose. In the medium to long term, technological advancements will increase the organism's fermentation efficiency (producing more ethanol in less time) and resistance, requiring less hydrolysate detoxification.

There is some economic homework to be done both before and after the production of biofuels.

An inexpensive and efficient pretreatment process should have the following properties: (a) produce active cellulose fibers for the enzymatic attack, (b) avoid destruction of hemicellulose and cellulose, (c) avoid the formation of hydrolytic enzymes and fermentation, avoid microbial inhibitors, (d) reduce energy requirements, (e) reduce the cost of reducing the raw material size, (f) reduce the material cost of building the pretreatment reactor, (g) reduce residue emissions, and (h) reduce energy consumption. Many pretreatment techniques for lignocellulosic materials have been proposed. Physical pretreatment, physical and chemical pretreatment, and biological pretreatment are four types of pretreatment processes (Karimi et al., 2006).

## 8 Discussion and Future Scope

Many people believe that biofuel is a cleaner option to cover all the transportation sector's energy needs. We benefit the environment by reducing $CO_2$ emissions in proportion to $CO_2$ absorbed from the atmosphere during engine combustion. As a result, the C cycle becomes closed. Despite the benefits of using biofuels, it's crucial to note that their production and usage have major environmental repercussions, including forest destruction, increased soil degradation, decreased food production, and the use of a lot of water. As natural resources are depleted and the population grows, natural habitat is being lost faster. In many places, water scarcity is already a limiting factor in food production. Sugar cane, for example, is a biofuel crop that requires more water and is monoculture, leading to pollution and scarcity of water. Water resources are overdrawn due to the demand for water for biofuel production, which is already strained and will become more so in the future. To fulfill future oil demands, developing countries like India prioritize implementing alternative fuel choices. The most diversified seaweeds are found around the Indian coasts; thus, they can be used for this purpose. In India, seaweed cultivation has been used for generations as a source of food, food derivatives, vitamins, proteins, and raw material for various agar–agar and algin-based enterprises. In order to meet nations' economic needs, biofuels must be cultivated on a big scale, and extraction technologies must be thoroughly explored.

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# Biofuel Projects and Current Environmental Policies: Vietnam's Case and Neighboring Asian Countries

**Tuan-Dung Hoang, Pham Thi Ha, Anthony Halog, Fayaz A. Malla, and Suhaib A. Bandh**

## 1 Introduction to Biofuel and Environmental Impacts

### *1.1 Definition of Biofuels*

In the mid-1970s, there was an increasing interest in biofuels when Brazil and USA started producing ethanol from sugarcane, though the consumption of biofuels had started in the late nineteenth century, and developed up to 1940s (ERIA, 2014).

According to ERIA (2014), biofuels are burnable fuel that originated in newly produced biomass such as food, fiber, wood, grasses, and crop residues, as well as industrial and municipal wastes, contrast to ancient biomass, which provides oil products. Technically, there are two wide groups of biofuels, including bioethanol (mainly refers to ethanol) which is an alcohol, and biodiesel which is an oil.

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## 1.2 Classification of Biofuels

Lee and Lavoie (2013) categorized biofuels into three groups including, first generation, second generation, and third generation based on the type of feedstock used to produce either ethanol or biodiesel.

Food sources for first-generation ethanol/biodiesel include soybean, rapeseed (canola), sunflower, palm, cane, and corn, as well as other less prevalent foods including wheat, barley, and sugar beet (USEPA, 2010).

Second-generation ethanol/biodiesel is produced from non-edible oils such as specialized biofuel grasses, agricultural leftovers, and wood chips, with the bulk coming from jatropha, according to Bhuiya et al (2014). Jojoba, karanja, moringa, castor, soapnut, and cottonseed oil are other sources of second-generation biodiesel, according to Atabani et al. (2012).

Algae (a single-cell organism) such as freshwater algae, marine algae, or wastewater algae are commonly used to make third-generation ethanol/biodiesel. Algae is chosen for producing either ethanol or biodiesel depending on its own characteristics (Wilkie et al., 2011).

Furthermore, "advanced biofuels" refers to ethanol created by innovative biofuel production processes from waste materials, wheat and maize stalks, wood, and specific energy crops (IEA Bioenergy Task 39).

## 1.3 Environmental Impacts of Biofuels

The effects of biofuels on the environment can occur at different stages of production and use as well as at different scale from the local, regional, national to global systems; some effects are easily identified while others are hardly noticed. The main environmental impacts of biofuels are considered in terms of global warming potential, agricultural land, water resource, impacts on soil resources, and biodiversity.

***Global warming potential***

Sources of biofuels can generate greenhouse gas emission differently depending on the production of feedstock, category of crops, location, and the fuel processing. The fossil energy used for feedstock production and transport is considered the main cause contributing to greenhouse gas emission. The fertilizer and pesticide manufacture, cultivating and harvesting of the crops or biofuel production plant demand for fossil fuel consumptions. According to FAO (2008), when nitrogen fertilizers are used in the progress, emissions of nitrous oxide effect on the greenhouse gas emissions are approximately 300 times stronger than carbon dioxide.

***Agricultural land***

The expansion of biofuel production affects the land-use change when there is an improved land productivity or expansion of cultivated area. At the same time, the development of agricultural techniques such as cows farming, agricultural soils, and rice production also results in the greenhouse gas emissions. FAO (2008) stated that the growth in global agricultural commodity production has been significantly caused by the increasing cropped area and regularity of cultivation. Additionally, the growth of demand for biofuels has far exceeded the rate of demand agricultural commodities and crop yields.

***Water resource***

Biofuel crops will affect the quality and quantity of water due to the changing of plants on crops as well as the application of fertilizer, and the treatment of wastewater. If the wastewater of production of biodiesel and ethanol released remain untreated, it could lead to the rise of eutrophication of surface water bodies. It should be noted that the adverse impacts of biofuels on soil and water from leakage and spill are possibly less far-reaching than that of fossil fuels due to ethanol and biodiesel are biodegradable (FAO, 2008).

***Impacts on soil resources***

Farming techniques play a crucial role in reducing the bad influences of the land-use change and the intensification of agricultural production on soils. The unsuitable farming practices can lead to a decrease in soil organic matter, while it might increase the erosion of soil due to the removal of permanent soil cover. The residue subtraction will result in losing of soil carbon, reducing soil nutrient contents, and accordingly increasing greenhouse gas emissions.

***Biodiversity***

Harish et al. (2020) believed that the biodiversity is greatly linked to the biofuel production in three main aspects, including feedstock used, scale of production, and management practices. The adjustment in habitat, degradation, excessive nutrient load along with cultivation of invasive alien species used as feedstock will lead to biodiversity loss.

## 2 Biofuel Programs and Environmental Policies in Vietnam

### *2.1 Biofuel Programs in Vietnam*

Biofuels are ready to be competitive, and they can play a role in underdeveloped countries (Hubbard, 2010). Biofuels come in a variety of forms, including solid (fuelwood, charcoal, wood pellets, or briquettes) and liquid (bioethanol or biodiesel) (World Energy Council, 2016). Biodiesel and bioethanol are the most practical biofuels for automobiles now being investigated internationally (Liaquat et al., 2010).

Biomass is a vital source of energy for a more sustainable civilization. Nature, on the other hand, has developed a wide variety of biomass that may be utilized for

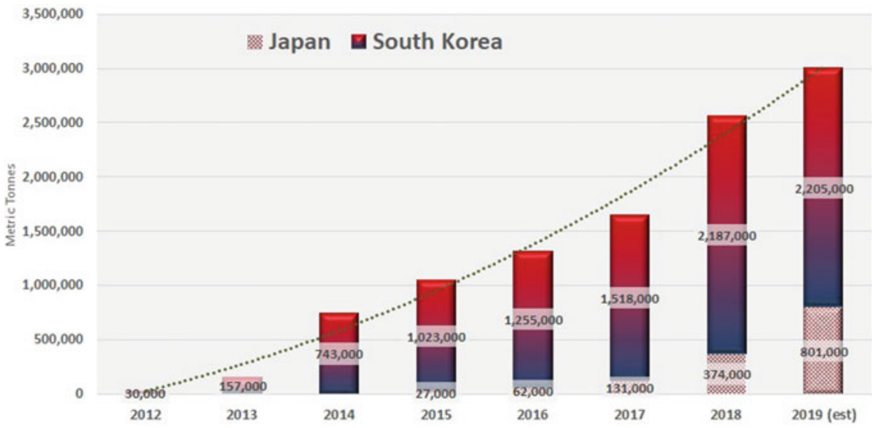


**Fig. 1** Vietnam wood pellet exports to Japan and South Korea

both industrial and home purposes. As a result, various natural and human influences influence the content and qualities of biomass. Some of these need to be significantly improved before they can be used as a sustainable fuel in highly efficient biomass-to-energy networks (Bergman & Kiel, 2005).

Several writers have looked on biofuel production, according to the Asian Development Bank in 2009. Soybean, sesame, used oils, fish oil, and jatropha may be used to make biodiesel, whereas sugarcane, maize, rice, and cassava can be used to make ethanol. In Vietnam, Nguyen et al. (2018) discovered that biodiesel synthesis from waste cooking oil (WCO) was initially done in a static mixer reactor with sodium hydroxide as a catalyst. The biodiesel obtained complies with European and Vietnamese biodiesel requirements.

Aside from liquid biofuel, solid biofuels have increased in quantities in the region. For instance, Vietnam's wood pellet production has also increased significantly over the past five years and the output of wood pellets exported to Japan and South Korea have exceeded 3 million metric tons in 2019 (see Fig. 1).

Molasses from sugar mills are the most common raw material used in industrial bioethanol production in Vietnam. Only one facility in Vietnam now produces ethanol from both cassava and molasses. The proportion of ethanol from molasses is quite minor (3–6%), and around 100 million tons of ethanol are produced yearly in Vietnam (Trinh and Linh Le, 2018). Molasses typically comprises between 40 and 45% sugar (Hieu, 2016).

## 2.2 *Environmental Policies in Vietnam*

Since 2007, the Vietnamese government has pushed the production and use of E5 and B5 in the local market, directing the development of bioenergy or biofuel sectors. As part of this strategy, the Vietnamese government approved the Strategy for Biofuel Development in 2015 and Vision 2025 in November 2007 (Trung et al., 2016).

The Prime Minister's Decision No. 2068/2015/QD-TTg details Viet Nam's Renewable Energy Development Strategy in the stage of 2030 perspective to 2050. According to this approach, biofuel production for the transportation sector's fuel need will increase from around 150 thousand TOE in 2015 to roughly 800 thousand TOE in 2020; 3.7 million TOE in 2030; 10.5 million TOE in 2050, corresponding to 25% of the transport sector's fuel demand.

As a result, by 2030, Vietnam is forecast to cut fossil fuel imports by around 40 million tons of coal and 3.7 million tons of oil products (APERC, 2016). The Vietnam Politburo of the Communist Party's has issued a resolution No. 55/NQ-TW, 2020 on "the direction of Vietnam's energy development strategy to 2030 with a vision to 2045." The resolution focused on prioritizing exploitation and the complete efficient use of renewable energy sources, new energy, and clean energy. In 2018, the consumption proportion of E5 gasoline in Hanoi and Ho Chi Minh City had increased to about 40% of the total gasoline consumption (Vietnam Biennial update reports, 2021).

Furthermore, since 2003, the Vietnamese government has been formulating and releasing supportive policies for the growth of biofuels (Asian Biomass, 2013). The National Energy Production Strategy to 2020 with a Vision to 2050 was formed in 2007, with the goal of accelerating the development of new renewable energy and phasing out fossil fuels. Short-, medium-, and long-term plans were developed in accordance with this concept. The strategies cover the following topics: (1) improving research and development, (2) establishing a strong industry that uses agricultural products to produce biofuels, (3) developing policies and frameworks that will attract investors (both domestic and international) to establish vibrant biofuel industries, and (4) promoting international cooperation to help the biofuel sector (Trinh and Linh Le, 2018). The government has granted tax advantages for local and foreign enterprises to import new equipment in keeping with this policy. Companies who invest in this sector are also awarded land for a 20-year term. A variety of legislative frameworks for formulating and executing policies related to environmental protection have been adopted and developed based on the 2013 Constitution of the Socialist Republic of Vietnam (Table 1).

## 3 Development in Environmental Perspective of Biofuels Projects in Southeast Asia and China

Most of the nations in Asia depend significantly on the supply of imported oil, whereas they must cope with the population explosion, rising income levels as well as expanding urbanization. Thus, biofuels have become an important subject in their energy policies when not only can diversify the sources of imported liquid fuels but also increases jobs for their people. Moreover, biofuel production can contribute

**Table 1** Legal documents addressing environmental protection in Vietnam

| Law and legal policies on environmental protection | |
|---|---|
| Decree 03/2015/ND-CP | Assessment of environmental damage |
| Decree 18/2015/ND-CP | Environmental protection masterplans, environmental assessments, environmental impact assessment, and environmental protection plan were detailed |
| Decree 19/2015/ND-CP | More detailed law on environmental protection was mentioned |
| Decision 18/2013/QD-TTg | Environmental improvement and rehabilitation as well as environmental payment were introduced such as in the activities of mineral extraction |
| Decision 78/2014/QD-TTg | Vietnam environment protection fund was organized |
| Circular 27/2015/TT-MONRE | Strategic environmental assessment, environmental impact assessment, and environmental protection plans were developed |

The abbreviations in the document are defined as follows: *MONRE* ministry of natural resources and environment; *CP* government; *ND* decree; *TT* circular; *TTg* prime minister; *QD* decision

partly to the policy of decreasing the prospects of $CO_2$ reduction. According to International Energy Agency (2014), the share of biofuels will increase from 1.5% in 2012 to 2.9% by 2035 in its current policy scenario, though it must reach 8.9% by 2035 in its $CO_2$ emission stabilization scenario. The prospect of biofuel consumption will take over the use of fossil oil gradually in Asia.

### *3.1 Southeast Asian Countries*

When it comes to the consideration of energy security and agricultural benefits, the production and consumption of biofuels have become a crucial objective in the Association of Southeast Asian Nations (ASEAN), especially in Indonesia, Malaysia, Philippines, Thailand, and Vietnam. There are significant differences in biofuel feedstock resources, market size, and demand in these countries. However, they have existing comprehensive biofuels policies in Asia. For instance, Indonesia and Malaysia have massive prospects for biodiesel production from palm oil thanks to the rich sources of palm oil trees of this nation, while they do not have a lot of potentials in bioethanol production. By contrast, Thailand has plenty of bases in producing bioethanol correspondingly with a huge domestic market; however, there is a limitation in resources of producing biodiesel due to the scarcity of palm plantation in Thailand.

Kumar et al (2010) believed that Indonesia is a prominent producer of first-generation biodiesel from palm oil plantations. In addition, Indonesia is also a key feedstock for producing advanced biodiesel in the future from empty fruit bunches and shells. Palm oil residues and rice husks have been used to generate power. A

10-megawatt (MW) plant in Riau and a 3-MW plant in Lampung, are two clear examples, respectively. Furthermore, the additional feedstock in Indonesia might increase from rapidly growing tree species (Table 2).

**Table 2** Potential biofuel production pathways for Indonesia (Kristiana & Baldino, 2021)

| Pathways | Feedstock | Fuel types | 1st or 2nd generation | Typical blending constraints |
|---|---|---|---|---|
| Biodiesel/fatty acid methyl ester (FAME) | Palm, used cooking oil (UCO), coconut, soybean, jatropha, animal fats | Biodiesel | 1st | 5–10% in most countries, but currently higher in Indonesia |
| Hydroprocessing | Palm, UCO, coconut, soybean, jatropha, animal fats | Drop-in fuels, e.g., hydrotreated vegetable oil (HVO) or renewable diesel, and hydroprocessed esters and fatty acids (HEFA) | 1st | None |
| Conventional bioethanol | Sugarcane, molasses, sweet sorghum, cassava, corn | Ethanol | 1st | 5–15% |
| Cellulosic ethanol | Palm residues, rice straw, corn stalks, sugarcane bagasse, cassava stems, biological portion of municipal solid waste, demolition wood | Ethanol | 2st | 5–15% |
| Gasification—Fischer–Tropsch synthesis | Natural gas, coal, petroleum coke, and the same kind of biomass as is used for cellulosic ethanol | Drop-in fuels, e.g., renewable diesel, jet fuel, gasoline | 1st | None |

(continued)

**Table 2** (continued)

| Pathways | Feedstock | Fuel types | 1st or 2nd generation | Typical blending constraints |
|---|---|---|---|---|
| Anaerobic digestion | Palm oil mill effluent (POME), biodegradable waste, livestock manure, sewage sludge, agricultural residue, food waste | Biogas (which can be combusted into electricity or cleaned and compressed into methane) | 1st | None |

Similarly, Malaysia is also a significant producer of biodiesel from palm, and the production of advanced biofuel can develop from lignocellulose feedstock from the country's palm plantations (Fig. 2).

In the Philippines, sugarcane and molasses are used as feedstock to produce bioethanol while coconut oil is esterified for biodiesel plants (Yamaguchi, 2013). The country also has the potential for producing advanced biofuels from the giant agricultural sector, such as sugarcane bagasse or coconut residues.

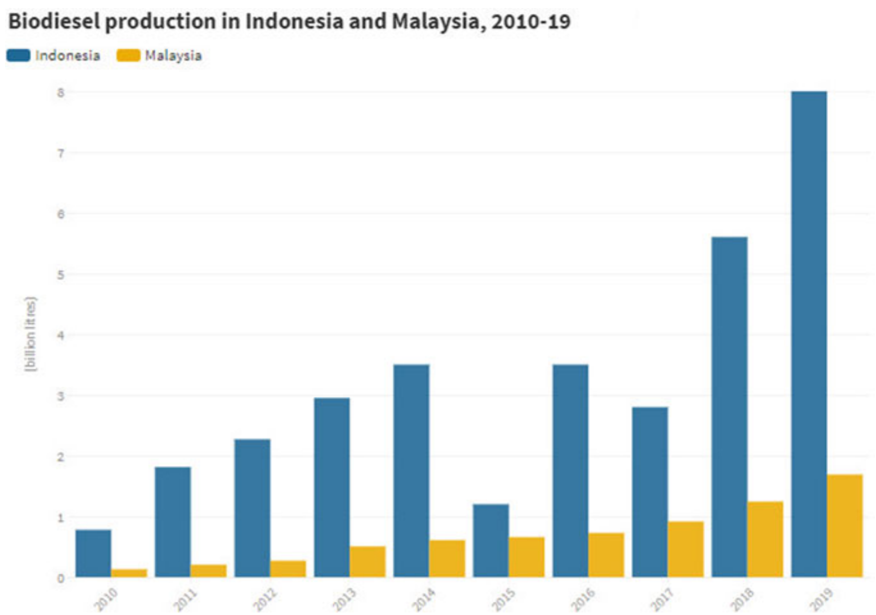


**Fig. 2** Biodiesel production in Indonesia and Malaysia, 2010–2019 (USDA, 2018)

Thailand has begun an energy initiative to generate power from agricultural left-overs. According to Kumar et al. (2010), 91% of Thailand's power was generated by sugarcane bagasse, rice husks, or wood at the end of 2008. Thailand's Ministry of Energy's Department of Alternative Energy Development and Efficiency estimates that biomass may offer 4400 MW of producing capacity. Alternatively, advanced biofuels might be made from a fraction of the wastes (Kumar et al., 2013).

Nguyen and Tran (2015) concluded that the main source of biofuels in Vietnam are paddy rice, sugarcane, and maize, while the amount of cassava, cotton, peanuts, and soy is much smaller.

The capacity and resources of producing biofuels are varying among ASEAN; therefore, a regional integrated market for biofuel trade across countries is expected to optimize the biofuel supply and demand in the region.

In ASEAN region, for the purpose of maintaining energy security as well as promoting sustainable development, the biofuel policy must be robust (Table 3).

Of the five ASEAN countries studied, Indonesia is the only one that has set a target for a bio-jet fuel mix of 5% by 2025 and 10% by 2050. Because biofuel has a more sustainable label than conventional fossil fuels like gasoline or diesel, sound biofuel development policies are required to ensure that large-scale biofuel quantities and qualities are produced and consumed in order to achieve both environmental and economic and social benefits.

## *3.2 China*

In China, the importance of biofuels has been detailed in the long-run strategic plan with the targets of protecting the natural environment and decreasing the dependence on imported energy. Nevertheless, China's policymakers only concentrate on ethanol, with ethanol programs supporting several national initiatives to manage air pollution (Xu et al., 2016). Hoang, T.-D.; Nghiem (2021) pointed out that China is big producers of ethanol in the world (Hoang, T.-D.; Nghiem, 2021).

In November 2015, the State Council published "The Energy Development Strategy Action Plan (2016–2020)" which designed to cap annual energy use as well as set a target by 2020, the rate of non-fossil fuel-based energy will be at least 15%, and ethanol is the most important element of this plan (Reuters, 2017).

According to China Biofuel Annual 2020, China limited its ethanol market up to the year of 2015 when it banned the import of ethanol and hardly allowed the extra production for export. In 2020, China ranked at the fourth position in producing fuel ethanol after the USA, Brazil, and the European Union. Meanwhile, it was estimated to be the fifth largest consumer of ethanol. Regardless, China withdrew from the global market in 2018 when additional duties on the US-origin imports were applied. Industry reports on main ethanol production facilities in China are listed in Table 4 and could add up to 2.8 billion liters in new production capacity if completed.

The major ethanol products of China are potable alcohol, medical grade, other industrial chemicals, as well as fuel ethanol; and the non-fuel industrial chemicals

**Table 3** ASEAN countries with comprehensive biofuel policy

| Country | Policy/strategy | The biofuel production target for the transportation sector | Government ministries/agencies |
|---|---|---|---|
| Indonesia | Indonesia National Energy Plan (Ministerial Regulation No. 22/2017)[1] | 30% biodiesel plan by 2025 (update: the government has announced B30 blending recently to start in January 2020[2] | Ministry of Energy and Mineral Resources (MEMR) |
| Malaysia | National Biofuels Policy 2006[3] | B5 program was launched in 2011 to encourage 5% biofuels blend (update: the government has announced the B10 biodiesel program starting December 2018)[4] | Ministry of plantation industries and commodities (MPIC) (renamed: ministry of primary industries) |
| Philippines N | National Biofuels Program (NBP)[5] | 1% ethanol blend by 2007, 2% by 2008, 5% by 2009, 10% blend by 2011 and increasing to 20% by 2020. Meanwhile, 5% biodiesel blend by 2015 and 20% by 2025 (update: current biodiesel blend is at 2%)[6] | Department of energy |
| Thailand | Alternative Energy Development Plan (AEDP) 2015–2036[7] | 25% RE share in the transportation sector by 2036 | Department of Renewable Energy Development and Energy Efficiency (2015), Ministry of Energy |

*Source* Ying (2020)

are the main end-use market, unlike the fuel ethanol from other ethanol-producing nations. In China, the main fuel ethanol is produced from corn-based, and then cassava-based and sugarcane-based, which is approximately 87%, and 11%, respectively. However, the new sources are examined to switch to cellulosic bioethanol, along with coal and industrial flue gas-based synthetic ethanol.

In terms of biodiesel, due to the stringent environmental regulations, biodiesel is developing fast (China Biofuel Annual, 2020). The growth per year of biodiesel is illustrated in Table 5.

It is also worth noting that the domestic demand for biodiesel in China is estimated to fall, due to the COVID-19 impact on transportation sectors in this country (China Biofuel Annual, 2020).

**Table 4** Production capacity of China's fuel ethanol licensed producer (China Biofuel Annual, 2020)

| | Production capacity of China's fuel ethanol licensed producers (2020 estimates) | | |
|---|---|---|---|
| | Producers | Production capacity | Feedstock |
| I | SDIC Jilin Alcohol | 887 million liters (700,000 tons) | Com |
| 2 | HenanTianguan | 887 million liters (1,700,000 tons) | Wheat. Com, Cassava |
| 3 | COFCO Biochemical (Anhui) | 798 million liters (630,000 tons) | Com, Cassava |
| 4 | COFCO Bioenerov (Zhaodono) | 507 million liters (400,000 tons) | Com |
| 5 | SDIC (Zhanjiang) | 190 million liters (150,000 tons) | Cassava |
| 6 | Shandong Longlive | 65 million liters (51,300 tons) | Com Cob |
| 7 | COFCO Bioenergv (Guangxi) | 253 million liters (200,000 tons) | Cassava |
| 8 | Zonerov (Inner Mongolia) | 38 million liters (30,000 tons) | Sweet Sorghum |
| 9 | SDIC (Tieling) | 380 million liters (300,000 tons) | Com |
| 10 | Liaoyuan Jufeng Biochemical | 380 million liters (300,000 tons) | Com |
| II | Jilin Boda Biochemistry | 507 million liters (400,000 tons) | Com |
| 12 | Jiangsu Lianhai Biotechnology | 152 million liters (120,000 tons) | Com |
| 13 | Shandong Fu'en Biochemical | 152 million liters (120,000 tons) | Cassava |
| 14 | Jiangxi Yufan | 127 million liters (100,000 tons) | Cassava |
| 15 | Shougang Lanza Tech | 58 million liters (46,000 tons) | Synthetic gas |
| 16 | SDIC (!Hailun) | 380 million liters (300,000 tons) | Com |
| 17 | Wanli Runda | 380 million liters (300,000 tons) | Com |
| 18 | Hongzhan (Huanan) | 380 million liters (300,000 tons) | Com |
| 19 | Ningxia Shougang Lanza Jiyuan | 57 million liters (45,000 tons) | Synthetic gas |
| | Total | 6578 million liters (5.2 million tons) | |

*Source* Industry Sources

**Table 5** Biodiesel growth per year in China (China Biofuel Annual, 2020)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Biodiesel (Million liters)* | | | | | | | | | | |
| Calendar Year | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020f |
| Beginning stocks | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Production | 738 | 927 | 1079 | 1133 | 787 | 909 | 1043 | 834 | 939 | 1455 |
| Imports | 0 | 49 | 895 | 1028 | 33 | 8 | 18 | 853 | 953 | 60 |
| Exports | 0 | 0 | 0 | 43 | 27 | 76 | 194 | 357 | 752 | 715 |
| Consumption | 738 | 976 | 1974 | 2118 | 793 | 841 | 867 | 1330 | 1140 | 800 |
| Ending Stocks | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Production capacity (Million liters)* | | | | | | | | | | |
| Number of Blorefiner1es | 49 | 52 | 53 | 53 | 53 | 48 | 46 | 44 | 40 | 42 |
| Nameplate Capacity | 3400 | 3600 | 4000 | 4000 | 4000 | 2680 | 2680 | 2680 | 2680 | 2726 |
| Capacity Use (%) | 21.7% | 25.8% | 27.0% | 28.3% | 19.7% | 33.9% | 38.9% | 31.1% | 35.0% | 53.4% |
| *Feedstock use for fuel (1000 MD)* | | | | | | | | | | |
| Used Cooking 011 | 722 | 907 | 1055 | 1108 | 771 | 891 | 1022 | 816 | 918 | 943 |
| *Market penetration (Million liters)* | | | | | | | | | | |
| Biodiesel, on-road use | 221 | 270 | 324 | 340 | 236 | 273 | 313 | 410 | 430 | 250 |
| Diesel, on-road use | 121,479 | 131,797 | 133,383 | 133,365 | 134,375 | 130,564 | 130,538 | 126,898 | 135,370 | 136,149 |
| Blend Rate (%) | 0.2% | 0.2% | 0.2% | 0.3% | 0.2% | 0.2% | 0.2% | 0.3% | 0.3% | 0.2% |
| Diesel, total use | 186,890 | 202,765 | 205,205 | 205,177 | 206,730 | 200,868 | 200,828 | 195,228 | 208,262 | 209,460 |

## 4 Conclusions

As evidenced by current international and local initiatives and actions, biofuels have been prioritized globally and in Asia. When considering the use of biofuels to reduce fossil energy usage and greenhouse gas emissions, the complete life cycle of biofuel production must be addressed. Many studies have found that second-generation technology can greatly improve the greenhouse gas balance of biofuel production.

When forests or grasslands are removed to make way for farms in order to create biofuel feedstocks, however, carbon that has been stored in the soil is released into the sky. As a result, when biofuels are used to replace fossil fuels, the advantages are negative, resulting in a net increase in greenhouse gas emissions. In actuality, the worldwide consequences of increased biofuel production will be highly dependent on where and how the feedstocks are grown, as well as whether or not appropriate agricultural practices are used.

The creation and production of biofuels can have an impact on biodiversity. Natural landscapes such as grasslands and rainforests are destroyed and transformed into energy-crop plantations, or peatlands are drained, resulting in habitat loss. Biofuel crops, on the other hand, can have a beneficial influence in some cases, such as when they are utilized to repair damaged areas.

When it comes to water resource effect, crops for biofuel development and production need irrigation, which puts a strain on local water supplies. Soil erosion and runoff including fertilizers and pesticides can also have an impact on water quality.

In terms of soil quality, the consequences will vary depending on how the area is farmed. Soils may be harmed by changes in land use and agricultural production methods. Some strategies, as well as the use of specific plant species, can help to mitigate negative effects and even enhance soil quality.

Biofuels are predicted to add to the worldwide supply of transportation fuels as well as total energy sources in terms of energy security. Because agricultural markets are limited in comparison to energy markets, rapidly increasing biofuel production would raise agricultural feedstock prices, making them uncompetitive versus petroleum-based fuels.

Developing cost-effective methods for converting lignocellulosic feedstocks into advanced biofuels has been a priority for Southeast Asian countries (IRENA, 2017). Furthermore, nations with a substantial natural resource base, such as Malaysia and Indonesia, can generate and process feedstock at a competitive price. They can create a biofuel industry that is commercially feasible.

Due to its plentiful biofuel feedstocks, Indonesia has the ability to create biofuels via a variety of pathways employing various biochemical and thermochemical processes. Indonesia is the world's biggest producer of first-generation biodiesel, with palm oil plantations as the raw material, and empty fruit bunches and shells as a crucial feedstock for advanced biodiesel production. By the end of 2021, PT Pertamina, an Indonesian state-owned oil corporation, wants to produce all of its diesel and jet fuel from palm oil. Pertamina plans to process 3000 barrels of palm oil per day for biodiesel by December, and by December 2022, production will have doubled to 6000 barrels per day for biodiesel and jet fuel. In 2023, Indonesia plans to build a second refinery with a capacity of 20,000 barrels per day (Reuters, 2021b).

Malaysia is a big biodiesel producer as well. Palm and lignocelluloses are used as feedstock. Palm plantations in the nation might be an ideal feedstock for advanced biofuel production. Under Malaysia's National Biofuel Policy 2006, known as the NBP, the Malaysian government aims to encourage palm oil production and the use of palm-derived biodiesel, particularly in the transportation and industrial sectors.

The Philippines features a number of bioethanol plants that use sugarcane or molasses as a feedstock. Biodiesel factories based on the esterification of coconut oil exist in the Philippines. Approximately, 80% of the country's total molasses is utilized to make ethanol.

Thailand has put a lot of effort into researching the energy-generating potential of agricultural waste. Thailand's ethanol policy encourages the use of gasohol (ethanol–gasoline mixes) by providing price incentives and a tax break for automobiles that can run on E20 and E85 gasohol.

Agricultural residues such as paddy rice, sugarcane, and maize provide substantial amounts of biofuel in Vietnam, whereas cassava, cotton, peanuts, and soy produce tiny amounts. According to Nguyen and Tran (2015), there is also a large amount of managed forest that might be used for biofuel production. During the first half of the year, the country consumed 1.78 million cubic meters of biofuel E5 RON 92 (Bio-fuels International, 2018). This is a 31% increase over 2017 and accounts for more than 40% of total fuel consumption in Vietnam.

Since the early 2000s, China has emphasized biofuel production and usage (Hoang, 2021). The Chinese government has set lofty goals for itself, aiming to produce 12.7 billion liters of ethanol and 2.3 billion liters of biodiesel year by 2020. China's ethanol and biodiesel production quantities were still limited in 2015, with only 3.08 billion liters of ethanol and 1.14 billion liters of biodiesel produced (Hoang, 2021). China is now the world's third-largest bioethanol producer (Hoang, 2021).

In conclusion, while biofuels are a great alternative to fossil fuels and a possible solution to energy security challenges, there is still a need for biofuel production regulation and policy. The development of biofuels may create greater harm to the land and more environmental concerns if no policy or control is in place. Good agricultural practices and strategies to guarantee sustainability characteristics should be used uniformly for all crops to provide an ecologically sustainable production of biofuel. Furthermore, each government must consider the environmental implications of biofuel production. Because the ability and resources for generating biofuels differ throughout ASEAN, a regional integrated market for biofuel trading among nations is likely to emerge to optimize the region's biofuel supply and demand.

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# Biofuels an Option for Reducing Ecological Footprint

**Jinnath Rehana Ritu, Saleha Khan, Ranga Rao Ambati, and Ravishankar Gokare Aswathanarayana**

## 1 Introduction

The world's population is growing continuously and is expected to reach 9.8 billion by 2050 (Sarkodie et al., 2019). The population growth is burdening the environment and natural resources endangering the health of the planet. The ecological footprint is a method that is mainly used to measure human demand for natural capital and to sum up the sustainability of the resources. Moreover, Kitzes and Wackernagel (2009) stated that ecological footprint analysis is the sustainability assessment that determines the sum of biologically fertile land and sea requisite for a set population or activity. Due to rapid industrialization, urbanization, modernization, and to cope with energy demand for the whole world, the ecological footprint value is increasing preposterously. Adoption of biofuel based energy system can be a strong approach for the reduction of ecological footprint in multifarious ways (Fig. 1).

Biofuel is an excellent source of energy obtained from biomass resources as fuel for transportation, power generation, heat production and many other energy needs. Global expansion of biofuel may be the solution to over come the obstacle of energy crisis in ensuring human development and economic growth, by reducing the GHG emissions in a carbon-negative manner (Matsuda & Takeuchi, 2018).

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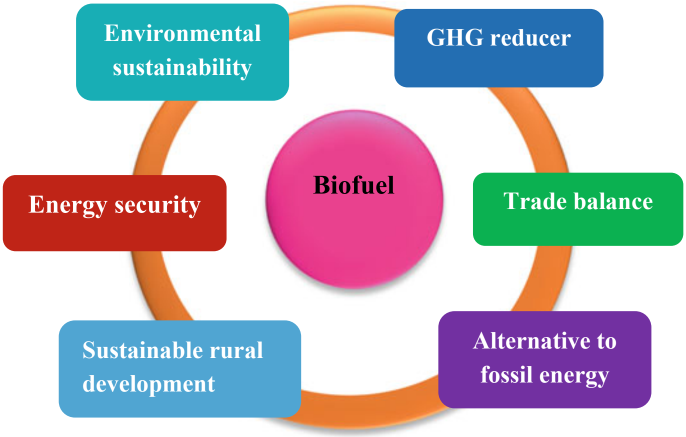


**Fig. 1** Multifarious contribution of biofuel in reducing the ecological footprint

Countries throughout the world are now aiming to curtail emissions in accordance with sustainable development goals set by the UN (United Nations, 2017). Currently, there are over a billion vehicles around the world that are anticipated to double by 2050, causing a great deal of GHG emissions to nature (Zahedi et al., 2019; Mizik & Gyarmati, 2021). Therefore, the adoption of the biofuel production approach can reduce the dependence on fossil fuels and import of oil for domestic needs. In addition, it is possible to bring in trade equality by sustainably utilizing domestic resources by replacing fossil fuel with environment-friendly biofuel due to their renewable nature (Schmidt et al., 2016).

Hence, the adoption of biofuels is an excellent way of attaining sustainability of future fuel demands throughout the world because energy security is a base of real prosperity and advancement in the world. This chapter summarizes the multifarious contributions of biofuel in reducing ecological footprint underpinning the need to boost biofuel production by adopting policies, and providing subsidies/incentives to the enterprises by various governments.

## 2 Biofuel and Its Typology

Biofuel is a promising replenishable renewable energy source that is derived from plant material, animal waste and microalga. Biofuels are classified based on their feedstocks used and production process (Table 1) (Fig. 2). Among them, ethanol and biodiesel are the most commonly utilized biofuel that is derived from crop plants.

Biofuel GHG reducer Alternative to fossil energy Trade balance Sustainable rural development Energy security Environmental sustainability.

**Table 1** Types of biofuels [Modified from Jeswani et al. (2020) and Hossain et al. (2019)]

| Types of biofuels with feedstocks | | | Products during biofuel production | |
|---|---|---|---|---|
| 1st generation | 2nd generation | 3rd generation | Final products | By-products |
| Food crops | Energy crops | Microalgae | Bioethanol<br>Biodiesel<br>Biogas<br>Butanol<br>Dimethyl ether<br>Dimethylfurane<br>Hydrogen<br>Methanol<br>Mixed alcohols | Glycerine<br>DDGS<br>Electricity/heat |
| Corn<br>Wheat<br>Sugar beet<br>Sugar cane<br>Palm oil<br>Rapeseed oil<br>Soya bean oil<br>Sunflower oil | Miscanthus<br>Switchgrass<br>Poplar<br>Willow | *Chlorella vulgaris*<br>*Botryococcus braunii*<br>*Nannochloropsis* sp.<br>*Chlorococum* sp.<br>*Chlorella* sp.<br>*Chlamydomonas reinhardtii*<br>*Ostreococcus tauri* | | |

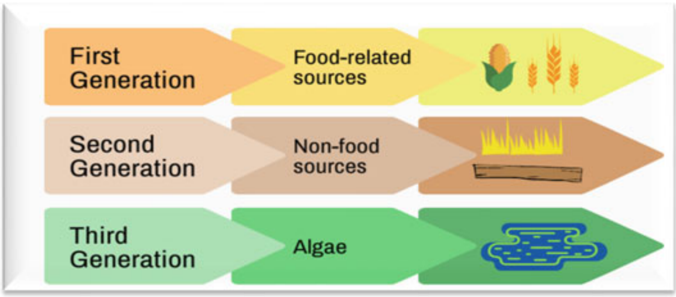


**Fig. 2** Infographics showing three generations of biofuel (Gunathilake and Let's talk Science, 2019)

## 3 Biofuels an Option for Reducing Ecological Footprint

The smaller value of footprint than biocapacity infers idealistic condition for attaining sustainability of humanity where larger value than biocapacity shows growing $CO_2$ emissions, economic development, rising income, and higher consumption by using resources unsustainably which cause severe depletion of natural resources. The highest ecological footprint is found in Luxembourg, which is near about 15.82, having lions share from its carbon footprint, where biocapacity per capita is 1.68, and total biocapacity deficit per capita is −7.35. The top 20 countries owing higher ecological footprint value have been shown in Fig. 3. Contrariwise, China has the largest value of total biocapacity deficit of −3435.62 with an ecological footprint of 3.38 (Countries by Ecological Footprint, 2021). As a consequence, outpacing human demand on ecosystem services should be diminished by using energy-saving approaches. Biofuel can be an ideal candidate for addressing global demand if the shortcomings of biofuel production are minimized through proper policies and planning.


**Fig. 3** Highest ecological footprint of top 20 countries (Data taken from Countries by Ecological Footprint, 2021)

### *3.1 Reduction of Greenhouse Gas Emission*

According to the IEA report, in 2021, near about 1.5 billion tons of carbon dioxide are anticipated to be produced, which will make a surge in the history as a second largest increase where a reverse condition is found in 2020 due to the COVID-19 pandemic, which is a dire warning for the world recovery (IEA, 2021) (Fig. 4). Mitigating this higher amount of $CO_2$ is now a dire need to make the world habitable and as enriching as before. Although $CO_2$ emissions reduced in 2020, the concentration of major GHGs such as $CO_2$, $CH_4$ and $N_2O$ is increasing in both 2019 and 2020 (UNEP, 2020).

Reviving the present unsustainable economy to a sustainable one, replacing fossil fuel by biofuel is a stirring phenomenon worldwide concerning the envisaged objective of reducing GHG emission into the atmosphere coupled with providing environmental, social and economic welfare. United States Department of Agriculture showed that starch-based biofuel is capable of mitigating GHG emissions by 43% than conventional gasoline that can be on upward pace by 50% by 2022, and cellulosic biofuel has the potentiality to lessen 85–95% GHG emissions over gasoline baseline 2010 (POET (Winter, 2018)) (Fig. 5). Due to its carbon–neutral nature, biofuel effectively reduces GHG emissions (Hanaki & Portugal-Pereira, 2018).

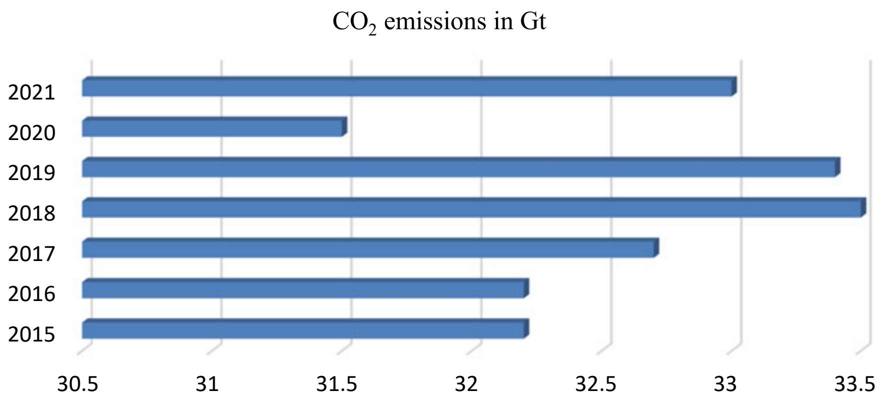


**Fig. 4** Global energy-related $CO_2$ emissions (Data taken from IEA, 2021)

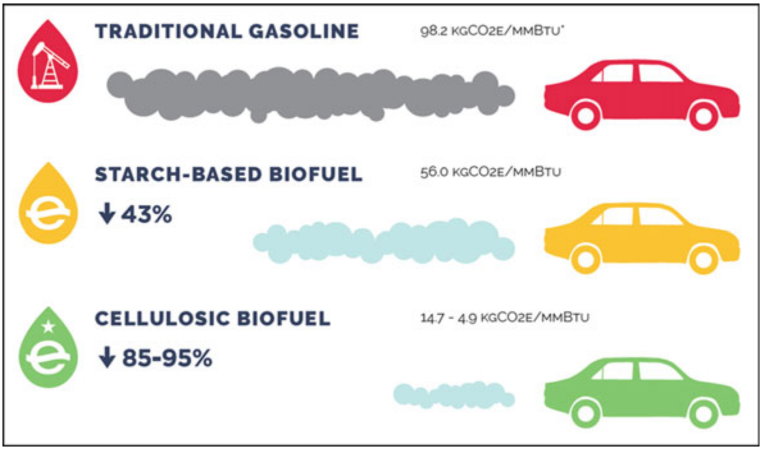


**Fig. 5** Benefits of biofuel in reducing GHG emissions (POET (Winter, 2018))

## *3.2 Curtailment of Imported Fossil Energy*

The usance of fossil fuels is on the ascent with the revolutionary changes in the economy of the world mainly burned for electricity, heat and transportation purposes which act as a significant driver of climate change. Chia et al. (2018) stated that fuel demand will increase at 1.4% annually, which will continue until 2040. Moreover, 96.3% of fuel utilized in the transport sector comes from fossil fuels (IEA, 2019). As a result, the transport sector will be responsible for carbon emissions up to 80% in 2030 (Mussatto, 2016). It is also assumed that if timely steps are not taken to bring down this critical situation, carbon emissions will double by 2040 (Subramaniam &

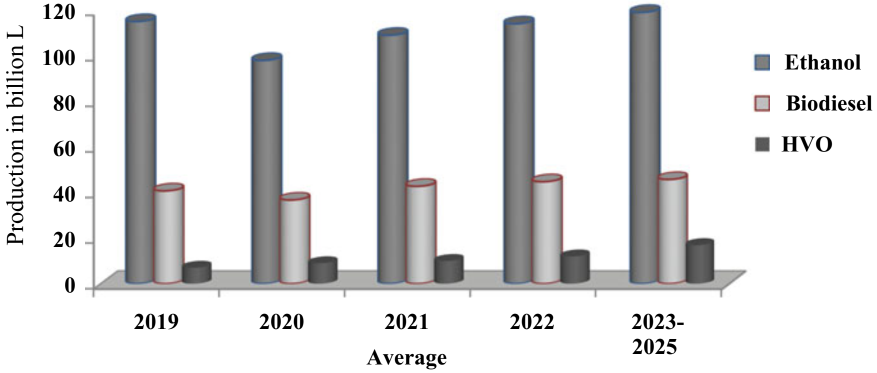


**Fig. 6** Global biofuel production in 2019 and forecast to 2025 (Data taken from IEA, 2020)

Masron, 2021). Utilization of biofuel instead of using fossil fuel may be a credible route to combat climate change which consummately helps to maintain ideal ecological footprint value. Already biofuel programs have been launched in more than 60 countries, and they are trying to blend biofuels in their fuel bucket (IRENA, 2016). World biofuel production is being forecasted to be also in increasing trend (Fig. 6), which helps to reduce dependence on imported fossil fuel and minimize its price volatility by ensuring global energy security as well as economic globalization (Owusu & Asumadu-Sarkodie, 2016) because in most of the developing countries fossil fuel covers half of its import bill. Hence, adopting biofuel production approaches is a core need to curtail reliance on fossil fuels.

## *3.3 Trade Balance*

The trade of biofuels is on the onward trend to envisage the global need for renewable fuels, which in increasing trend is affected by policies, tariffs and crop yields. The current significant participants in the liquid biofuels trade are the USA, the EU, Brazil and Argentina. Mandates or targets should be adopted to invigorate the biofuel production rate that will play an essential role in keeping balance in trade. The USA and Brazil contribute about 89% to the global bioethanol production where the EU and USA play a leading role in the world's biodiesel production as well as some east Asian countries like the Philippines (biodiesel), Thailand and Vietnam (ethanol) also have been rising their biofuel production (Takeuchi et al., 2018). Their participation in increasing biofuel production triggers the trade balance of respective countries that potentially helps in reducing ecological footprint as well. Moreover, the upliftment in the bioethanol sector plays an important role in increasing average annual real GDP growth in Mozambique (Leitner et al., 2017).

It is of great worth that the expected market size of biofuel is approximately increasing trend from US$ 141.32 billion in 2020 to US$ 307.01 billion by 2030, including a CAGR of 8.3% from 2021 to 2030 (OTTAWA, 2021). Consequently, most developed countries, along with emerging economies throughout the world, are aiming at the production of biofuels to knock off the subserviency on fossil fuels that is expected to aggravate the growth of biofuel, which will be a core driver in lessening ecological footprint.

### *3.4 Sustainable Rural Development*

The preface of the new industry generates a wide range of lucrative opportunities, which strengthens the sustainable development of human and economic capital as well. The biofuel industry is such a potential tool replacing old forms of energy generation for achieving this delicate prosperity as it is closely interrelated to the economy, environmental protection, employment, food, feedstock production, innovation and technology. Biofuel production also has a great impact on farm incomes, and its supply chain propagates circular rural income by uplifting socio-economic and health conveniences of rural people and cutting down the import dependence on energy (HT Correspondent, 2020) (Fig. 7). Multifaceted policy-making steps are being endorsed to increase the potential and timely use of biofuels, which have immense potential. For instance, India's biofuel policy aims to generate rural employment and development to achieve energy self-sufficiency and security by sustaining environmental improvement. Thurlow et al. (2016) found that biofuels cannot accelerate economic growth and reduce poverty by merely ensuring improved food security by creating crop diversification and higher-income outputs from rural people in Tanzania but can be achieved by involving them in substantial participation in feedstock production to processing into the final product. The EU executive also anticipated that job opportunities and economic activity would be created through the biofuel production chain (Michalopoulos, 2017). Thus, biofuel develops the lifestyle of rural people to divert them from fossil energy consumption to renewable ones that contribute to ecological footprint size.

### *3.5 Mitigation of Environmental Pollution*

Cameron et al. (2004) stated that automotive emissions are avowed as a core source of air pollution than any single human activity. Thereby, an alternative energy source is needed that will be successful in lower-emitting GHG by lessening pollution and keeping the environment pollution free that is a way of maintaining ecological footprint value. The accession of biofuel to conventional fuels may abate the emissions of some pollutants generating from transportation (Subramanian et al., 2018;

**Fig. 7** A great contribution of biofuel in creating jobs and economic activity results in substantial socio-economic benefits for communities [**a** is taken from Michalopoulos (2017), and **b** is taken from HT Correspondent (2020)]

Thiyagarajan et al., 2017a, 2017b) significantly of particulate matter which is originated by combustion of diesel (Kumar & Subramanian, 2017; Thiyagarajan et al., 2017a, 2017b). The IEA reported that when bioethanol is added to gasoline, it can successfully lessen carbon monoxide emission and reduce carbon hydride and particulate matter, which helps mitigate environmental pollution (Takeuchi et al., 2018). Moreover, biodiesel can lower the exhaust emission of particulate matter, carbon monoxide, hydrocarbons and volatile organic compounds, which is keeping contribution by preserving better environmental quality and sustainability due to its zero net emittance carbon dioxide (Fig. 8). Another study conducted by NASA revealed that biofuel minimizes the pollution of the jet engine by improving airline economics and the environment also (NASA, 2017).

**Fig. 8** Biofuels are effective in preserving environmental quality by reducing pollution (taken from Bose, 2020)

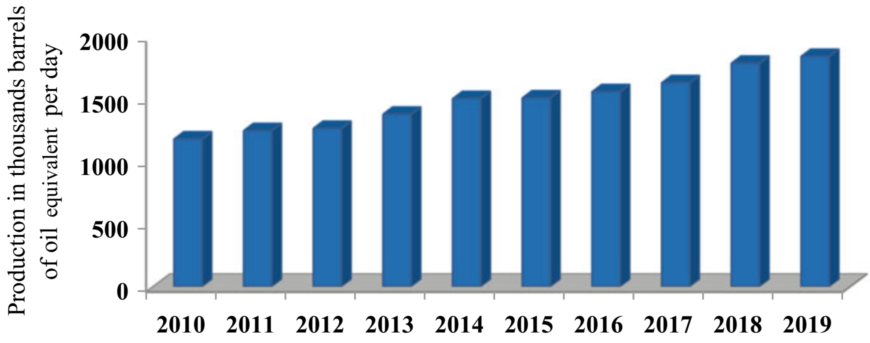


**Fig. 9** World biofuel production (2010–2019) (Adopted from Sonnichsen, 2021)

## 4 Global Energy Security

The Sustainable Development Goals 7 ensures that energy is clean, affordable, sustainable and accessible to all and may be obtained with a potentially crucial renewable energy source. In attaining energy security in the world, biofuel can be considered an integral option of a sustainable portfolio that ensures better access to environment-friendly energy to the people in demand for the smooth running of the economy. Now, sustaining energy security has become the critical propeller of biofuel production in most developing countries. According to the report showed by Sonnichsen (2021), global biofuel production levels rise to 1841 thousand barrels of oil equivalent per day, which were only near about 187 thousand barrels of oil equivalent per day in 2001 that indicates that proper, timely policies for biofuel production can be a way of attaining energy security that consummately reduces ecological footprint too due to its reduced environmental impacts than fossil fuels (Fig. 9). On the contrary, the USA, Brazil, Indonesia, China and France are the leading five countries that consumed biofuel, among which only the USA consumed 1067.48 thousand barrels per day of biofuel in 2019 (Fig. 10). Therefore, increased biofuel production by minimizing unsustainable issues of biofuel will be a solid candidate to ensure energy security by balancing production and consumption.

## 5 Biofuel and Environmental Sustainability

Environmental sustainability is an important phenomenon to conserve environmental quality by preserving natural resources efficiently and conserving global ecosystems to uphold health and wellbeing for the future generation. Moreover, sustainable energy is defined as a dynamic harmony between the equitable availability of energy-intensive goods and services to all people and the preservation of the earth for future

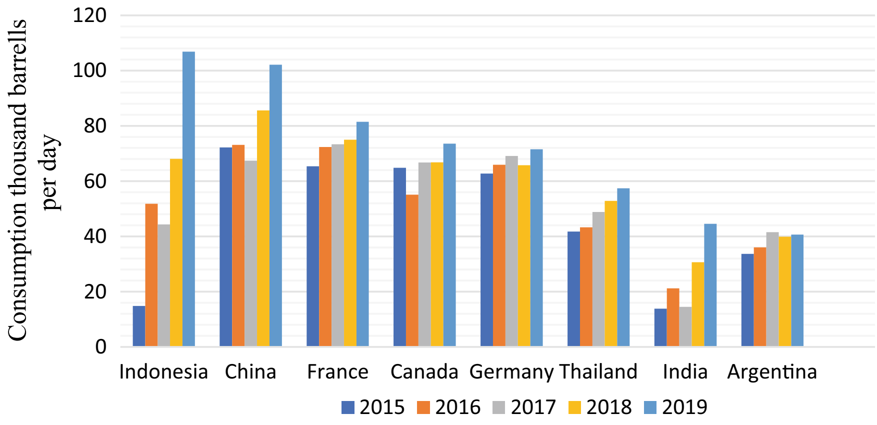


**Fig. 10** Total biofuel consumption by top 10 countries (World Data, 2020)

generations (Tester, 2005). Biofuels will be a dynamic resolution to sustain the environmental quality that makes biofuels come out on top. Especially for biofuel, there are three pillars of sustainability, including environmental, economic and social; those should be appropriately analyzed to reveal more beneficial impacts than detrimental effects (Esteves et al., 2020). It is also reported that biofuels can burn cleaner than fossil fuel, usually not responsible for producing any kind of sulfur or aromatics and any unpleasant smell during the burning of biofuels which also exert GHG at a reduced level than other conventional fuels and act as a carbon sink while growing (Strickland, 2012). Subramaniam et al. (2020) also added that biofuels can offer the opportunity to upgrade environmental health, which also helps in incrementing food security.

## 6 Conclusions

In every aspect of human life, energy is a mandatory part of keeping the wheel of economic development and productivity moving. To subside environmental conditions from the higher pressure of increasing food production, energy consumption and economic upliftment, renewable resources have become a global concern. Overall, biofuels are considered sustainable substitutes, offering innumerable prospects in maintaining a smaller carbon footprint which is considered a more significant part of measuring ecological footprint by keeping a healthy environment and mitigating climate constraints, dependency on fossil energy and enhancing welfare and poverty curtailment effectively. For addressing crucial climate change issues, sustainability, energy security and reducing ecological footprint, government's support in the form of subsidies and incentives is a dire need for expanding the biofuel industry. Furthermore, a modern integrated approach, more sustainable solutions, complete value chain analysis, international cooperation and partnership, extensive research on sustainability issues of biofuel should be conducted that makes it as a conventional fuel in future from today's alternative biofuel.

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# Biofuel in Constructing Green Circular Societies: Circular Biorefinery of TPOMW

**Consolación Sánchez Sánchez, Francisco Cuadros Blázquez, Almudena González González, and Francisco Cuadros Salcedo**

## Abbreviations

| | |
|---|---|
| AD | Anaerobic Digestion |
| $BOD_5$ | Biological Oxygen Demand |
| COD | Chemical Oxygen Demand |
| EI | Equivalent Inhabitants |
| HRT | Hydraulic Retention Time |
| IRR | Internal Rate of Return |
| NPV | Net Present Value |
| PRI | Period of Return on Investment |
| TPOMW | Two-Phase Olive Mill Wastewater |
| OMWW | Olive Mill Wastewater |
| OWP | Olive Mill Wastewater without Polyphenols |
| SS | Suspended Solids |
| TS | Total Solids |
| VFAs | Volatile Fatty Acids |
| VDS | Volatile Dissolved Solids |
| VSS | Volatile Solids in Suspension |

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## 1 Introduction

In the last 60 years, olive oil production has tripled with the IOC member countries producing 2,062,000 t, or 93.8% of the global total in the 2020/2021 season (International Olive Council, 2019).

The production of the group of European countries would have reached 1,924,100 t, a decrease of 15% compared to the previous campaign (2019/2020).

In Spain, production would have been 1,125,300 t (−37.1%), in Italy 366,000 t (+ 110.8%), in Greece 275,000 t (+ 48.6%) and in Portugal 140,500 t (+ 40.1%). Production in the other IOC member countries will have increased by 32.9%, reaching a total of 1,084,500 t. Tunisia stands out with 350,000 t (+ 150%), followed by Turkey with 225,000 t (+ 16.3%), Morocco with 145,000 t (−27.5%) and Algeria with 125,500 t (+ 29.4%) (see Fig. 1). In addition, the world consumption of olive oil is also increasing annually due to olive oil's high nutritional and oxidative value (International Olive Council, 2019).

Practically 100% of olive oil extraction is done using the so-called two-phase extraction process. This process generates a by-product, Two-Phase Olive Mill Wastewater, TPOMW, (alperujo in Spanish). Its composition is given by parts of the olive but also by the remains of the olive oil. It has a more solid part, which is the pomace, and a more liquid part, which is the alpechín. Its properties include a high water content of 56%. It also has an acid PH of 5.4 and a high organic matter content of 91%.

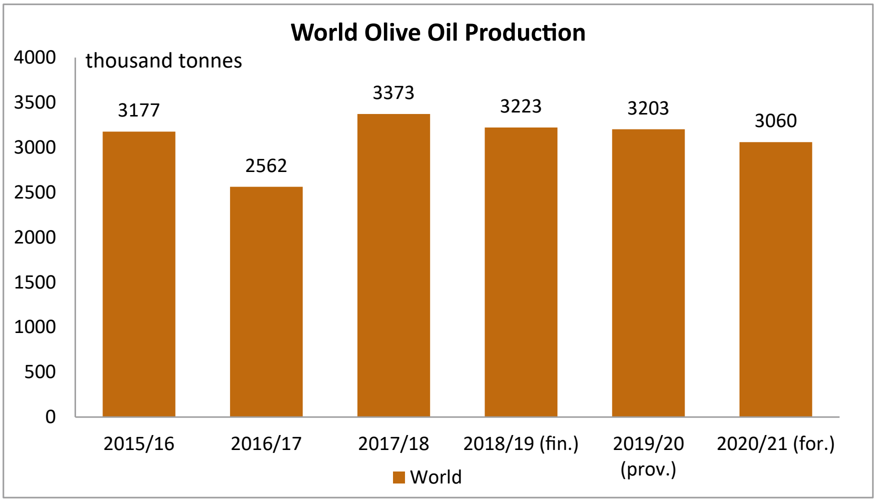


**Fig. 1** Evolution of world olive oil production (International Olive Council, 2019. *Note* excl. pomace oil)

The indiscriminate dumping of TPOMW causes major problems of discolouration of the waters where it is deposited, negative effects on aquatic ecosystems, phytotoxicity, bad smells and, consequently, soil pollution (Araújo et al., 2015). Specifically, of the total amount of olives processed, 75% corresponds to olive pomace and only 25% to olive oil.

Alperujo has a density of 890 kg/m$^3$ (Aqualia Connections, 2019) and has a biological oxygen demand of about 40 g $O_2$/L (Cuadros et al., 2011; Seoánez, 2003). According to the European Directive 91/271/CEE (Directive Europe, 1991), on wastewater treatment, it is established that 1 equivalent inhabitant (EI) has a biodegradable organic load with a $BOD_5$ equivalent to 60 g of $O_2$/day (Sánchez-Sánchez et al., 2020). If the TPOMW is not properly managed and knowing the polluting power of the TPOMW, the overall pollution impact produced in the 2020–2021 campaign can be quantified by the following Eqs. (1–5).

Therefore, the pollution generated by the TPOMW would be equivalent to that generated by some 25,119,386 equivalent inhabitants. Worryingly, forecasts point to an increase in these products in the coming years. Taking these data into account, the impossibility of indiscriminate dumping has made it necessary to determine what to do with these by-products. The most common methods currently used are discussed in the following section.

$$\frac{\text{g } O_2}{\text{year}}(\text{BOD}_5 \text{ per inhabitant}) = \frac{\text{g } O_2}{\text{day}} \times \frac{n^0\text{days}}{\text{year}} \tag{1}$$

$$\frac{\text{g } O_2}{\text{tonne}_{\text{TPOMW}}} = \frac{\text{g } O_2}{\text{L}}(\text{BOD}_5) \times \frac{\rho_{\text{TPOMW}}(\text{L})}{\text{kg}} \times \frac{1000 \text{ kg}}{1 \text{ tonne}} \tag{2}$$

$$\frac{\text{tonne}_{\text{TPOMW}}}{\text{year}} = \frac{\text{tonne}_{\text{olive oil produced}}}{\text{year}} \times \frac{4 \text{ kg}_{\text{TPOMW generated}}}{\text{kg}_{\text{olive oil produced}}} \tag{3}$$

$$\frac{\text{g } O_2}{\text{year}}(\text{BOD}_5 \text{ per TPOMW}) = \frac{\text{tonne}_{\text{TPOMW}}}{\text{year}} \times \frac{\text{g } O_2}{\text{tonne}_{\text{TPOMW}}} \tag{4}$$

$$\text{EI} = \frac{\text{g } O_2}{\text{year}}(\text{BOD}_5 \text{ per TPOMW}) / \frac{\text{g } O_2}{\text{year}}(\text{BOD}_5 \text{ per inhabitant}) \tag{5}$$

## *1.1 TPOMW Treatment Options*

After an extensive bibliographic review of chemical, physical, biological and combined treatment technologies to adequately manage the generated TPOMW (ElMekawy et al., 2013), two of them have been selected to study in this paper (Niaounakis & Halvadakis, 2004; Orive et al., 2021). In addition to the environmental impact, the increasing energy prices from fossil fuels are challenging the food industry and fine chemicals to find new technologies and new process strategies to reduce energy use and maximize the valorization of raw materials for economic sustainability (Munjur et al., 2018).

Biotechnology that can deal with this environmental problem is the AD or biomethanization of these residues. The problem lies in the fact that TPOMW and OMWW have a high concentration of polyphenols, a potent bactericide that inhibits bioreaction, preventing bacterial growth and finally causing the death of these microorganisms. In previous studies carried out by our Research Group (González-González & Cuadros, 2013, 2015; Moreno et al., 2017*),* an attempt has been made to address this problem by pretreatment or by co-digestions with other substrates to reduce the concentration of polyphenols to limits in those that the bioreaction was stable.

This eco-friendly trend was followed by several researchers (Azbar et al., 2008; Gelegenis et al., 2007; Gonçalves et al., 2012).

Therefore co-digestion of TPOMW using anaerobic microbial degradation could be suggested as an acceptable economic and ecological solution for the safe disposal of TPOMW.

However, if the goal is to value only TPOWM, the biorefinery concept must be addressed.

Biorefinery is a concept defined, according to the International Energy Agency (IEA) Bioenergy Task 42, (Energy Information Administration Bioenergy, 2014) as "the sustainable processing of biomass into a spectrum of marketable products and energy". The biorefinery is an industrial facility, or network of facilities, that covers an extensive range of combined technologies aimed at the full sustainable transformation of biomass into building blocks with the concomitant production of biofuels, energy, commodity or speciality chemicals and materials, preferably of added value (Goldfarb et al., 2017; Morais & Bogel-Lukasik, 2013). Such a concept can be applied to any industrial production, for example, extraction of natural products used as ingredients (food, personal and home care, pharmaceutics), food supplements (nutrition), or active compounds (pharmaceutics) (Rombaut et al., 2014).

This paper has a theoretical character and we propose a first approximation of the integrated biorefinery concept for an adequate TPOMW management: supercritical fluid extraction to recover polyphenols, followed by a biomethanation. The aim is to demonstrate that the biorefinery construction project is energetically, environmentally and economically feasible. Figure 2 shows the scheme of the biorefinery-AD plant. We will call this scheme circular biorefinery.

The two-phase mill generates, on the one hand, the extra virgin olive oil, and, on the other, a highly polluting by-product that is difficult to degrade (TPOMW).

TPOMW are separated by traditional physical procedures in their solid and liquid fractions. The solid fraction (50%), so-called orujillo in Spanish, can be dried and is a good biomass fuel (see Fig. 2).

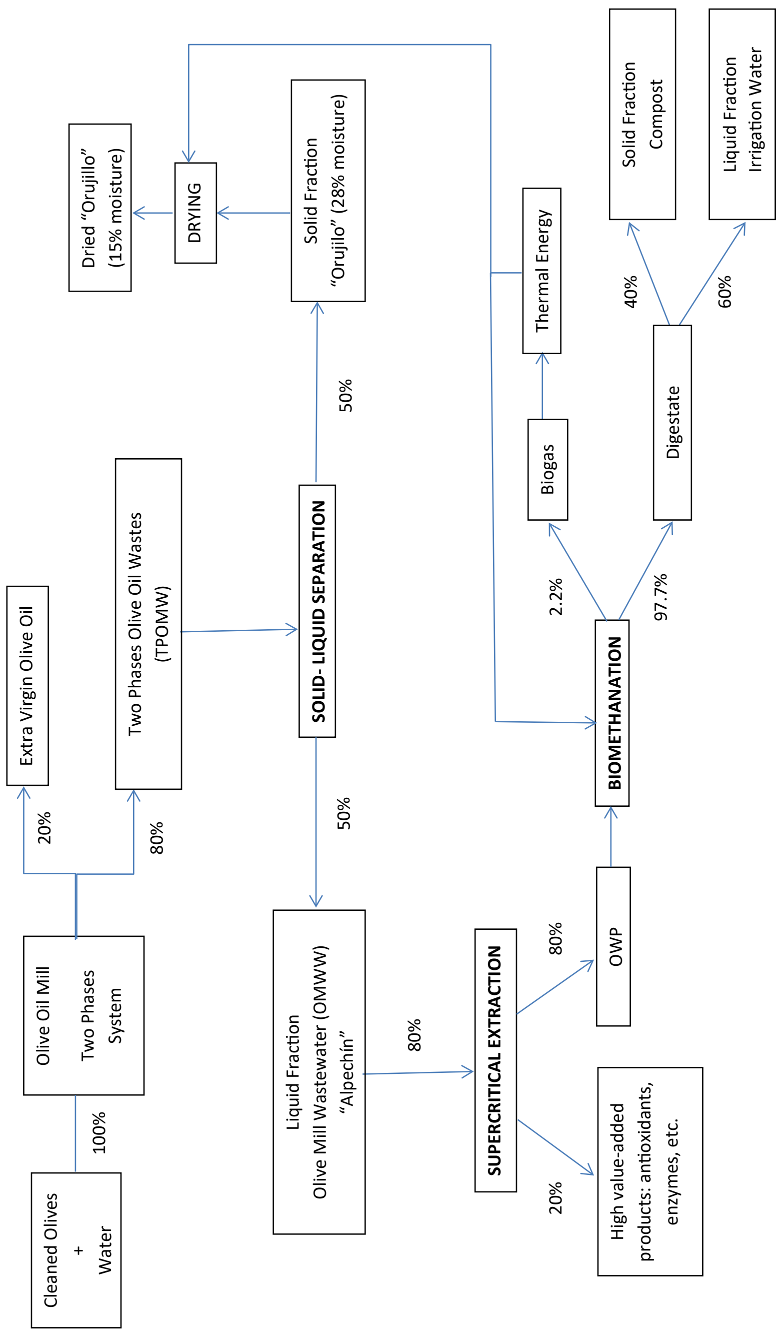


**Fig. 2** Scheme of a circular biorefinery of TPOMW

For its part, the liquid fraction from OMWW (alpechín in Spanish), the other 50%, serves as a raw material in the biorefinery to obtain substances of high added value (antioxidants, enzymes, etc.) There is currently a whole world of possibilities in terms of extracting TPOMW products with high added value: nutraceuticals, additives for animal feed, antioxidants, enzymes, activated carbon, etc. (Negro et al., 2017). This is the case of polyphenols that are powerful antioxidants for application in sectors such as food, or the pharmaceutical and cosmetic industry.

However, after the refining process of the TPOMW, there will be another type of waste, now already free of polyphenols or with such small concentrations, that we will call OMWW without polyphenols (OWP), which are optimal for its energetic, economic and environmental valorization (Circular Economy), without the need for any pretreatment.

The estimated production of these substances of commercial interest is around 20% by weight of the total OMWW. The effluents from the OMWW biorefinery (the remaining 80%) are OWP. OWP is now a susceptible by-product to be treated by biomethanation with guarantees and with the security that the bioreaction will not inhibit.

The biomethanation of the OWP gives rise, on the one hand, to green renewable energy (biogas), susceptible to being burned in a boiler and obtaining thermal energy. This thermal energy will be self-consumed in the biorefinery-AD plant complex: (i) to maintain the temperature of the anaerobic digester at 38 °C; (ii) to perform the drying of the solid fraction of the TPOMW.

The AD of OWP throws a digested sludge (Digestate), which, after filtration, is separated into a solid by-product (40% approx.) that can be composted and returned to the environment as an agricultural amendment, and in residual water (60% approx.), that can be used as irrigation water or returned to the sewerage network if it complies with current legislation; otherwise, it would be necessary to carry out a post-treatment until reaching the limits that the law contemplates. From experience, we know that this water can be used to irrigate fruit trees with which the fruit does not come into contact with it.

This review introduces a new and innovative area. To date, and our knowledge, there is no project in the world to build a biorefinery-AD complex to valorize and treat waste from the olive oil industry, such as the one proposed here. Therefore, it is presented as a new concept to face the challenges of the twenty-first century, to protect both the environment and consumers, and in the meantime to enhance the competition of industries to be more ecological, economical, and innovative.

The main objective of this work is to show that the construction of an AD plant adjacent to a biorefinery of the TPOMW is a technically possible and economically viable project in itself, independently of the good economic profitability of the biorefinery.

# 2 Analytical Methods

OMWW samples were taken to quantify pH, chemical oxygen demand (COD), alkalinity, volatile fatty acids (VFA), total solids (TS), volatile suspended solids (VSS) and volatile dissolved solids (VDS) according to the standard methods (APHA et al., 1992). The above procedure has been followed successfully in various papers published by our Research Group (González-González and Cuadros, 2013, 2014; Moreno et al., 2017).

## *2.1 Estimation of the Thermal Energy Potential*

The thermal power, $P_t$, generated by the combustion of the biogas obtained in the biomethanation is given by the following expression:

$$P_t(\mathrm{kW}) = ((P_{\mathrm{substrate}} \times P_{\mathrm{CH4}} \times \mathrm{CV}_{\mathrm{CH4}})/n) \times \eta \quad (6)$$

with $P_{\mathrm{substrate}}$ being the total amount of substrate (waste) to be treated, $P_{\mathrm{CH4}}$ is the production of methane obtained in laboratory AD trials measured in $\mathrm{Nm^3\ CH_4/m^3}$ of the substrate (*N* stands for normal conditions of pressure and temperature), $\mathrm{CV}_{\mathrm{CH4}} = 9.80\ \mathrm{kWh/Nm^3\ CH_4}$ the calorific value of methane, $n = 8760$ the annual number of hours of operation of the plant (equivalent to 365 days/year) and $\eta = 0.85$ the thermal efficiency of the boiler in which the biogas is burnt.

The total thermal energy, $E_t$, that would be obtained by burning the biogas generated during a year, is calculated through the Eq. (7),

$$E_t(\mathrm{kWh}) = P_{\mathrm{substrate}} \times P_{\mathrm{CH4}} \times \mathrm{CV}_{\mathrm{CH4}} \times \eta \quad (7)$$

## *2.2 Sizing the AD Plant*

A flow diagram of the proposed AD plant with all the equipment is shown in Fig. 3.

### 2.2.1 Mixing and Feed Tank Volume

After preparing the substrate, the mixture is passed to a feed tank with agitation so that the substrate is homogenized before entering the anaerobic digester. The volume of the feed tank will be oversized by 25% for safety reasons in agitation and aeration.

To size the mixing and feed tank, the treatment days (*d*), the total amount of substrate (waste) to be treated ($P_{\mathrm{substrate}}$) and the operating days of the plant per year

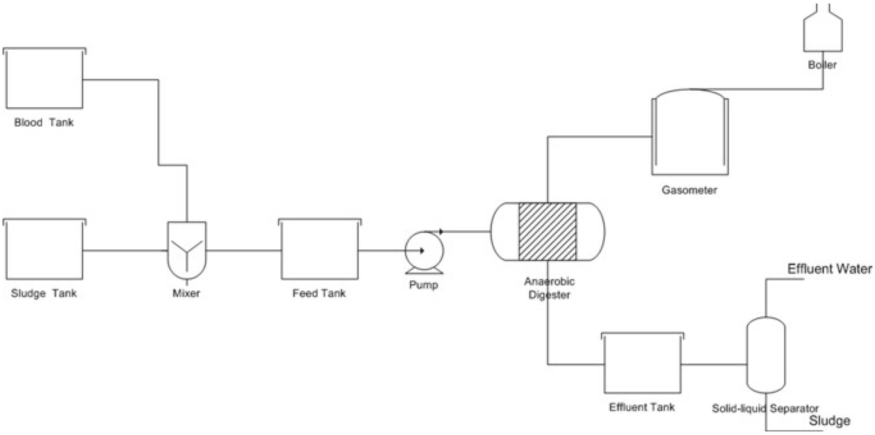


**Fig. 3** Flow diagram of the AD plant design (Cuadros Blázquez et al., 2018)

must be taken into account.

$$V_{\text{mixingandfeedtank}}\left(\text{m}^3\right) = \frac{P_{\text{substrate}}\left(\frac{\text{m}^3}{\text{year}}\right)}{\frac{\text{days}}{\text{year}}} * d * 1.25 \tag{8}$$

### 2.2.2 Digester Volume and Its Insulation

To calculate the volume of the anaerobic digester, the HRT of the substrate to be treated must be taken into account. To obtain this data, it is necessary to carry out a biomethanation experiment in the laboratory or to search in the literature for the optimum HRT of the substrate to be digested.

In addition, the amount of waste to be treated and the number of operating days of the plant per year must be known. Finally, 25% of the volume is added as a safety buffer.

$$V_{\text{anaerobicdigester}}\left(m^3\right) = \frac{P_{\text{substrate}}\left(\frac{\text{m}^3}{\text{year}}\right)}{\frac{\text{days}}{\text{year}}} * \text{HRT(days)} * 1.25 \tag{9}$$

In general, anaerobic digesters are cylindrical in shape, airtight and watertight; therefore, a very important aspect to consider when sizing the anaerobic digester is the required insulation surface of the reactor walls and base.

Therefore, the calculation of the wall and floor insulation is done using the lateral area and the base area of a cylinder.

$$\text{Wall insulation}\left(\text{m}^2\right) = 2\pi r * h \tag{10}$$

where $h$ is the height (m) and $r$ (m) is the radius of the digester.

$$\text{Floor insulation}\left(\text{m}^2\right) = \pi \times r^2 \tag{11}$$

where $r$ (m) is the radius of the digester.

### 2.2.3 Volume of the Digestate Storage Tank

After managing the by-products through the anaerobic digestion process, a digestate (effluent) is generated and must be stored. The sizing of the digestate storage tank is calculated for a capacity of normally two days.

$$\text{V}_{\text{digestate tank}}\left(\text{m}^3\right) = 2(\text{days}) * \frac{P_{\text{substrate}}\left(\frac{\text{m}^3}{\text{year}}\right)}{\frac{\text{days}}{\text{year}}} \tag{12}$$

### 2.2.4 Volume the Solid–Liquid Separator

To get the most out of the anaerobic digestion process, the digestate must be separated into two fractions: liquid and solid. The solid part is dried to be used as raw material for compost and the liquid part, if it complies with current legislation, can be used as fertilizer.

The separator is designed to run every 8 h per day. Therefore, the volume of the separator will be:

$$V_{\text{separator}}\left(\text{m}^3\right) = \left(\frac{P_{\text{substrate}}\left(\frac{\text{m}^2}{\text{year}}\right)}{\frac{\text{days}}{\text{year}}}\right) / \left(\frac{24\text{ h}}{8\text{ h}} * 1\text{ day}\right) \tag{13}$$

### 2.2.5 Gasometer Volume

A very important piece of equipment in an AD plant is the gasometer. The gasometer is a tank where the biogas (biofuel) generated by the process is stored before being used as an energy source for the industry's consumption.

To calculate its volume, it is necessary to know the energy yield of the reaction. This can be done by literature research or laboratory experimentation. In our case, it is assumed to have a storage capacity of two days.

$$V_{\text{gasometer}}\left(\text{m}^3\right) = \text{biogas production per AD}\left(\text{Nm}^3\ \text{biogas/day}\right) * 2\ \text{days} \qquad (14)$$

## *2.3 Economic Feasibility of the AD Plant*

One of the key aspects of analysing the economic viability of a biogas plant is to carry out a financial study. The main milestones to be considered are the initial investment, a forecast of fixed and variable costs and the income obtained. In addition, own and external resources must be taken into account.

### 2.3.1 Investment Estimate

Investment costs are defined as the sum of fixed capital (fixed investments plus pre-production capital costs) and working capital (or working capital), where fixed capital consists of the resources required to build and equip the biogas plant and working capital correspond to the resources required to operate the biogas plant.

To estimate the cost of the installation, the following must be known: costs of the AD plant's materials and equipment, administrative costs (authorizations and building permits), and other costs such as safety items, economic feasibility study and industrial advice, and those relating to commissioning.

### 2.3.2 Project Financing

Once fixed and working capital is estimated, it will be vital to have the necessary sources of finance to provide this capital. These sources of finance can be self-financing and equity participation (Loan financing).

In this case, according to the Decree 169/2016, dated October 18 (Ministry of Economy and Infrastructure, 2016), for the construction of a plant to manage this type of waste, a maximum subvention of 300,000 euros is available. In addition, we have also considered that the developer will apply for a bank loan equivalent to 75% of the total cost of the plant, with the developer's contribution being 25%.

### 2.3.3 Annual Outlay

The annual operating and maintenance costs we take to be 1.5% of the total cost of the plant.

For the bank loan amortization, we assume the loan requested to be for 15 years, at a mean interest rate of 2.5%. The plant's useful life is taken to be from 25 to 30 years.

### 2.3.4 Annual Revenue

This amount comes from the sale of dried olive pomace. This industry currently uses dried olive pomace a mean price of € 15/t (Biogramase, 2019).

### 2.3.5 Economic Parameters

Period of return on investment (PRI), net present value (NPV) and internal rate of return (IRR).

## *2.4 Estimation of Avoided $CO_2$ Emissions*

To assess the equivalent amount of $CO_2$ that is generated both by decomposing OWP waste naturally and by the anaerobic digestion process, two estimates are made: First, the volumes emitter of methane and carbon dioxide to the atmosphere, if OWPs are decomposed naturally or landfilled for putrefaction in one year, are considered to be the same as would be produced by AD (taking note that AD is only an acceleration, under controlled conditions, of the natural putrefaction process of organic matter). On the other hand, the rest of the trace gases obtained in AD are disregarded, considering only $CO_2$ and methane (González González & Cuadros, 2012).

Furthermore, according to the IPCC 2018, the global warming potential (i.e. the ability of the gas to trap heat in the atmosphere) of methane is considered to be 28 times higher than that of carbon dioxide for the next 100 years.

The calculation procedure is described below:

– Equivalent carbon dioxide emissions derived from natural degradation are the sum of Eqs. 18 and 19.

$$\frac{\mathrm{Nm^3CH_4}}{\mathrm{year}} = \text{waste generated}\left(\frac{\mathrm{m^3\ substrate}}{\mathrm{year}}\right) \times \text{ methane production by AD}\left(\frac{\mathrm{Nm^3CH_4}}{\mathrm{m^3\ substrate}}\right) \tag{15}$$

$$\frac{\mathrm{Nm^3CO_2}}{\mathrm{year}} = \text{waste generated}\left(\frac{\mathrm{m^3\ substrate}}{\mathrm{year}}\right)$$

$$\times\ CO_2\ \text{production by AD}\left(\frac{Nm^3 \text{biogas}}{m^3\ \text{substrate}} \times \%\ CO_2\right) \tag{16}$$

$$\text{Methane emissions}\left(\frac{\text{kg } CH_4}{\text{year}}\right) = \frac{Nm^3 CH_4}{\text{year}} \times \text{normal density of } CH_4\left(\frac{\text{kg } CH_4}{Nm^3 CH_4}\right) \tag{17}$$

$$\textit{Carbon dioxide}\ \text{emissions}\left(\frac{\text{kg } CO_2}{\text{year}}\right) = \frac{Nm^3 CO_2}{\text{year}} \times \text{normal density of } CO_2\left(\frac{\text{kg } CO_2}{Nm^3 CO_2}\right) \tag{18}$$

$$\text{Equivalent carbon dioxide emissions}\left(\frac{\text{kg}}{\text{year}}\right) = \text{methane emissions} \times 28 \tag{19}$$

– Equivalent carbon dioxide emissions derived from anaerobic digestion are the sum of Eqs. 20 and 21.

*Note* $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + 9.8\ \text{kWh/m}^3$ of $CH_4$ (the combustion of 1 mol of methane generates 1 mol of carbon dioxide)

$$\textit{Carbon dioxide}\ \text{emissions by combustion of methane}\left(\frac{\text{kg}}{\text{year}}\right) = \frac{\text{mole of methane generated by AD}}{\text{year}} \times \text{molecular weight of carbon dioxide} \tag{20}$$

$$\textit{Carbon dioxide}\ \text{emissions by anaerobic digestion}\left(\frac{\text{kg}}{\text{year}}\right) = \frac{Nm^3 CO_2}{\text{year}} \times \text{normal density of } CO_2\left(\frac{\text{kg } CO_2}{Nm^3 CO_2}\right) \tag{21}$$

The total equivalent carbon dioxide emissions avoided are the difference between the equivalent carbon dioxide emissions derived from natural degradation and the equivalent carbon dioxide emissions derived from AD.

# 3 Results and Discussion

## *3.1 Estimation of Energetic Potential of OWP by AD*

Until now, it has not been possible to perform a biomethanation of raw OMWW, due to its high concentration of polyphenols. As has been said, and despite its high water content, it is necessary to carry out some pretreatments before the bioreaction of such residues, such as (i) a dilution thereof of up to 30% OMWW/70% water; (ii) a subsequent aeration of this mixture until the concentration of polyphenols is such that it allows the stability of the bioreaction; (iii) control and adjustment of the pH of the said mixture (González-González, 2014; González-González & Cuadros, 2015; Moreno et al., 2017). These pretreatments make the AD process of OMWW more expensive, and, above all, large amounts of water must be added at the beginning of the process. The latter is not environmentally highly recommended: Water is increasingly a scarce commodity. Moreover, this addition of water considerably increases the size of the digesters and, therefore, increases the construction costs of the AD plant.

But in the case at hand, the OWPs that leave the biorefinery are free of polyphenols or have very small concentrations of them, which saves us these pretreatments (and their associated environmental and economic costs), in the case that the OWPs are treated through an AD process. This is the main idea underlying this work.

As can be seen in Fig. 2, 50% of 80% of the TPOMW that are treated in the biorefinery-AD complex are OWP (OMWW free of polyphenols). Based on previous results (González-González, 2014; González-González & Cuadros, 2015), as well as in the predictions of our mathematical model, which allows us to estimate the biogas production if we know the COD of the substrate, and assuming that the COD of the OWP is the same that of the raw OMWW (COD = 125.43 ± 2.90 g $O_2$/L. See Table 1), a minimum production of 32.31 $Nm^3$ biogas/$m^3$ OWP would be expected to obtain from biomethanization of the OWP. Finally, we will assume that this biogas obtained is composed of 65% $CH_4$ and 35% $CO_2$, and therefore, the expected biomethane yield would be 21.00 $Nm^3$ $CH_4/m^3$ of OWP.

## *3.2 Environmental Analysis: Estimation of CO2 Emissions*

To analyse the impact of the implementation of biogas technology, the following compares the equivalent $CO_2$ emissions that would be emitted if the OWP were decomposed naturally or incinerated with the equivalent $CO_2$ emissions if the waste is managed by anaerobic digestion technology.

Considering the estimates explained in Sect. 2.4. "Estimation of avoided $CO_2$ emissions", it is possible to quantify the positive environmental effect due to the reduction of carbon dioxide equivalent, a greenhouse gas, thanks to the sustainable process of biomethanization or anaerobic digestion (González-González, 2014; González-González & Cuadros, 2013).

**Table 1** Physicochemical characterization of OMWW

| | OMWW |
|---|---|
| Parameter | Values |
| pH | 4.12 ± 0.06 |
| CODtotal (g $O_2$/L) | 125.43 ± 2.90 |
| $BOD_5$ (g $O_2$/L) | 27.14 ± 3.13 |
| CODtotal (kg $O_2$/kg TS) | 1.20 ± 0.03 |
| $DBO_5$ (kg $O_2$/kg ST) | 0.26 ± 0.03 |
| Ratio $BOD_5$/COD | 0.22 ± 0.02 |
| Moisture (%) | 89.56 ± 1.82 |
| TS (%) | 10.44 ± 1.82 |
| VSS (g/L) | 46.40 ± 1.05 |
| VDS (g/L) | 35.71 ± 0.83 |
| VFA (g $CH_3COOH$/L) | 8.80 ± 1.00 |
| Alkalinity (g $CaCO_3$/L) | 1.85 ± 0.35 |
| Total polyphenols (g/kg ST) | 0.08 |

*$BOD_5$* biological oxygen demand, *COD* chemical oxygen demand, *TS* total solids, *VDS* volatile dissolved solids, *VSS* volatile solids in suspension, *VFA* volatile fatty acid

Following the estimates and equations in Sect. 2.4, it is possible to quantify the tonnes of $CO_2$ equivalents that would be emitted in a year by generating 5,500,000 $m^3$ of PMO. Thus, if this volume of waste were to degrade naturally and taking into account that methane is 28 times more efficient at producing global warming, a total of 2,315,428 t of $CO_2$ equivalent would be emitted by the natural decomposition of this waste.

When the pumps are powered by this biogas, the combustion of the methane content would give:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + 9.8\ \text{kwh/m}^3\ \text{of}\ CH_4 \qquad (22)$$

Assuming a boiler efficiency of 0.85 and using Eqs. 22, 20 and 21, 329,912 t of total $CO_2$ equivalents per AD would be obtained.

The analysis concludes that the adoption of anaerobic digestion technology would represent a good climate change mitigation practice, with a reduction of 1,983,665 t of $CO_2$ equivalents (86%) of emissions compared to natural degradation or incineration (Fig. 4). According to Pathak et al. (2009), biogas technology offers an excellent opportunity to mitigate greenhouse gas emissions and reduce global warming by replacing fossil fuels.

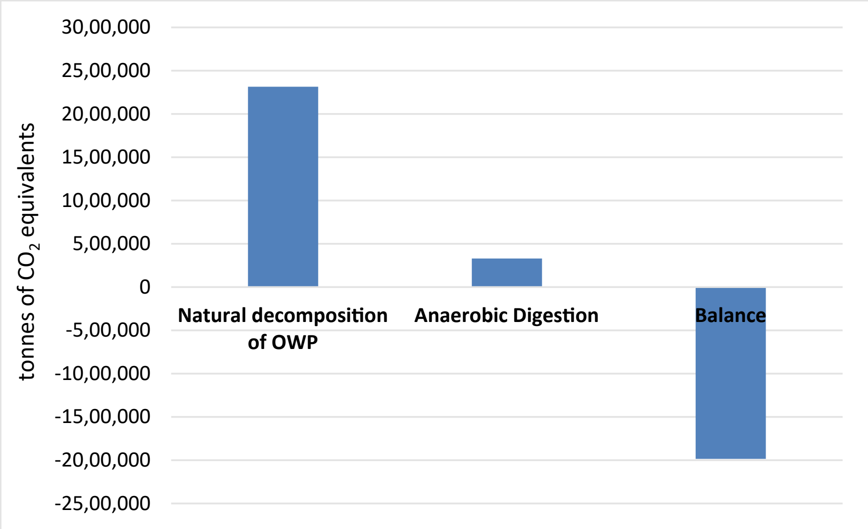


**Fig. 4** $CO_2$ equivalent emissions balance between natural decomposition and anaerobic digestion process

## 3.3 Energetic and Economic Benefits

In this section, we will carry out a sizing and an economic study of possible biogas plants that would treat the waste OWP obtained after the extraction of polyphenols from the OMWW. For this, the total average amount of TPOMW generated in most of the oil mills in Europe (100,000 t TPOMW/year) has been considered. This hypothetical AD industrial plant will treat about 40,000 t of OWP (Fig. 2). This volume of waste will be the starting point for sizing the biomethanation plant, whose main components are shown in Table 2.

So, we would have an average annual production of about 933,333 $Nm^3$ of biomethane/year. Considering a calorific power of 9.80 $kWh/Nm^3$ $CH_4$, the thermal energy contained in said biomethane would be about 9,146,667 kWh. To this amount

**Table 2** Sizing of the biomethanization plant of the OWP from an OMWW biorefinery

| Components | Characteristics |
|---|---|
| OWP storage tank | 43,000 $m^3$ |
| Two anaerobic digesters | 3500 $m^3$(each) |
| Mixing and feeding tank | 500 $m^3$ |
| Solid–liquid separator | 45 $m^3$ |
| Digested effluent storage | 350 $m^3$ |
| Gasometer | 1800 $m^3$ |

**Table 3** Summary of the feasibility analysis of the biomethanization plant OWP

| | | |
|---|---|---|
| Installation cost | Plant of anaerobic digestión (€) | 2,000,000 |
| | Own contribution (€) | 500,000 |
| | Bank loan (€) | 1,500,000 |
| Annual outlay | Maintenance of the plant (€) | 55,000 |
| | Bank loan (average 20 years) (€) | 65,465 |
| | Total cost (€) | 120,465 |
| Annual revenue | Dried "orujillo" sale (€) | 652,500 |
| | Total revenue (€) | 652,500 |
| Annual profit (€) | | 532,035 |
| Economic ratios | Period of return on investment (PRI) (years) | 3 |
| | Total NPV at 25 years (€) | 12,287,970 |
| | Internal rate of return IRR (%) | 38 |

should be subtracted the corresponding thermal energy used in maintaining the anaerobic digester at a temperature of 38 °C throughout the year. In that case, they would be available at 7,771,267 kWh. Taking into account that the average energy demand for the evaporation of the moisture content of the orujillo, assuming an efficiency in the drying of 80%, is 930 kWh/t of evaporated water (Cuadros et al., 2015), we would obtain annually about 43,500 t of dried orujillo. Considering an average sale price of dried orujillo of € 15/t (Biogramase, 2019), we would obtain an annual income of € 652,500.

The results of the economic feasibility study of the installation of the AD plant for thermal use in the complex biorefinery-AD plant are shown in Table 3. Here we can see that it has a return on investment period (PRI) of 3 years, an internal rate of return (IRR) of 38%, and a net present value (NPV) at 25 years of operation of € 12,287,970, which indicates that this installation would be economically profitable.

Finally, after the biomethanation of the OWP, the solid and liquid phases of the digested effluent (digestate) will be separated by filtering, the percentage of water thus recovered is around 60%. According to current Spanish environmental legislation, this water can be used to irrigate crops whose fruit does not come into contact with it, or to be dumped into the sewerage network. The wet solid fraction (40%), after undergoing a composting process, can be used as an agricultural amendment of excellent quality. It should be noted that in this work the economic input due to the sale of the agricultural amendment has not been considered.

This closes the extraction cycle of components with high added value of the OMWW, as well as the treatment and valorization of the OWP effluents that come out of said supercritical extraction (OWP) through their biomethanization. This scheme represents a new concept of circular biorefinery of olive oil residues that would help reduce (almost eliminate), in an economically profitable manner, the environmental impacts of this type of industries.

## 4 Conclusions

- The recovery of the polyphenols (antioxidants) contained in the OMWW through a supercritical extraction is a very favourable action for the subsequent biomethanization of the outflow effluents (OWP).
- The AD of the OWP could produce a total of 933,333 $Nm^3$ of biomethane/year, equivalents to 9.15 GWh/year of thermal energy that could be used to maintain the temperature of the anaerobic digester (38 °C) and to dry the solid fraction of the TPOMW.
- The estimated total cost of the plant is € 2,000,000 (VAT not included). Despite this high cost, the economic analysis showed that the construction of the AD plant would be economically profitable. The economic data ratify it: PRI = 3 years; IRR = 38%; and total NPV = € 12,287,970.
- The present study is of a theoretical nature, although taking some real data obtained by our Research Group in the laboratory and in the pilot plant. To obtain more conclusive results, it would be necessary to have real samples of OWP (liquid effluents leaving the biorefinery).
- To date, and to our knowledge, there is no project in the world to build a biorefinery-AD complex to valorize and treat waste from the olive oil industry, such as the one proposed here.
- The proposed project is an excellent example of Green and Circular Economy applied to the olive oil sector.

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# Transitional Framework from Conventional Fuels to Biofuels

**Ananya Roy Chowdhury and Achintya Das**

## 1 Introduction

Since wood was replaced by coal as fuel and subsequently by oil and gas, the following most significant change in fuel will be from oil and gas to renewable energy. In 1875, the first global coal-fired power plant was created in France (Song et al., 2021). With the development of human civilization, the coal industry grew to such an extent that in the late 1780s, wood was replaced entirely by coal, and coal took over the role of primary energy source. A technological revolution, the industrial revolution, and the development of machinery have greatly enhanced coal's use. With the advancement of the petroleum industry, coal-based steam engines were gradually replaced by diesel and petrol engines, especially after the development of external combustion engines. In the transportation sector, petroleum fuel dominates, while coal holds a dominant position in the power sector.

Nevertheless, those two fuel resources are responsible for a substantial amount of greenhouse gas emissions in the environment. Hence, there was a solid urge to shift from conventional fossil fuels to renewable energy sources. Thus, biofuel is one of the safer choices for sustainability and a low-carbon emission society under these circumstances. Growing environmental awareness creates a high demand for sustainable energy. More primary energy has been derived from natural gas and renewable resources. Over one-fifth of the global energy demand will be met by oil, gas, coal, and new resources by 2025 (Song et al., 2021).

It is undoubtedly a complicated procedure requiring a total shift in reliance on biofuel rather than conventional fuel. The globe is facing various natural threats,

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which are becoming more prevalent day by day. According to the World Meteorological Organization's (WMO) database, 2020 was one of the world's three warmest years (Khan et al., 2021). By 2070, worldwide transportation (measured in passenger kilometres) is predicted to have expanded fourfold, with motor vehicle ownership increasing by 60%. As a result, to meet the ever-increasing need for fuel energy, it is becoming increasingly important to find a quick solution to this problem, such as moving to biofuel. With the synthesis of biofuel by Henry Ford (1896) and subsequently with the invention of peanut oil by Rudolf Diesel, the idea of using biofuel was successfully tested (Khan et al., 2021). Biofuel is an excellent source of renewable energy made from algae, plants, and animal wastes. Biodiesel (fatty acid methyl ester (FAME), fuels from vegetable oils and fats) and bioethanol (synthesized from sugarcane, corn, and other crops) are two well-known biofuels among various biofuel sources. However, the role of renewable energy sources is far from being widespread.

## 2 Fossil Fuel

Energy consumption has skyrocketed in developing countries, reaching ecological carrying capacity and forcing humanity to choose several energy sources. As a result, the use of fossil fuels would rise on a global basis. Even though energy demand in developed countries has remained stable, it has quickly increased in Asia–Pacific emerging economies. Since the 1990s, energy use has polarized between East and West, rather than divided into three regions: North America, Europe, and Asia–Pacific. In 2014, North America, Europe, and the Asia–Pacific region consumed 21.3%, 20.1%, and 43.1% of worldwide fossil energy consumption, respectively. Demand for fossil fuels such as natural gas, oil, and coal has remained strong, while primary energy use has increased. Oil use has risen year after year, but non-renewable fuel consumption has fluctuated, with natural gas briefly displacing coal as the second-most-used fuel in 2015. As a result of decreased natural gas pricing in the United States over the last two decades, worldwide natural gas demand is expected to climb. Coal is one of the most widely used fossil fuels on the planet (Bank, 2020; Casper, 2010; Curley, 2011; Song et al., 2021; Zhukovskiy et al., 2021).

### *2.1 Petroleum*

Crude oil was used for various purposes other than fuel in ancient Sumerian, Assyrian, and Babylonian cultures. Liquid oil was also used as a wound dressing, liniment, and laxative by the ancient Egyptians. Oil-soaked arrows with fibres wound around them were used at the siege of Athens in 480 BCE. Spanish explorers discovered oil seeps in many places of the world, including Cuba, Mexico, Bolivia, and Peru, some centuries later. In North America, there are several oil seeps. Early explorers discovered them in New York and Pennsylvania, where Native Americans used the oil for therapeutic purposes. Due to the popularity of oil for illumination purposes, oil demand increased in the nineteenth century. In 1859, Edwin L. Drake drilled an oil well in northwest Pennsylvania. Other fresh oil fields were discovered in the USA, Europe, and East Asia within a short period (Curley, 2011).

Since the early twentieth century, oil production has had a significant impact on the increase of energy output, which is by far the largest reason for economic growth. Oil is an essential factor in international relations, and it has influenced foreign policy in the past. Thousands of barrels of oil are transported from producers to consumers every day. Petroleum is seen as a form of liquid gold.

***Petroleum Fuel Products*** These fuel products can be categorized mainly into three types, such as gaseous products, gasoline, and diesel.

### 2.1.1 Gaseous Product

Hydrogen, fuel gas, ethane, and propane are among the gaseous products of petroleum refineries. Refinery fuel gas is used to plant operations, and ethane can be recovered from the refinery fuel system as a petrochemical feedstock. As we all know, liquefied petroleum gas is used for domestic heating and cooking and light industrial purposes.

### 2.1.2 Gasoline

Gasoline is mainly used in the automobile sector for transportation purposes. Three main criteria to satisfy as a transportation fuel are as follows: (i) even combustion pattern, (ii) start quickly in cold weather, and (iii) reduce harmful tailpipe emissions from cars and trucks. Octane is a gasoline additive needed for the proper functioning of modern engines. Octane sources have taken many forms throughout the years, both renewable and petroleum based. They include lead, methyl tertiary butyl ether (MTBE), benzene, toluene, ethylbenzene, and xylene (BTEX), and ethanol (a biofuel). High octane rating is required for gasoline fuel to avoid premature ignition in the engine's cylinder and subsequent damaging in the engine (Stolark, 2016).

a. ***Lead***: In 1921, automotive engineers working for General Motors discovered that tetraethyl lead (better known as a lead) provided octane to gasoline, preventing engine knock. Leaded gasoline was preferred due to its lower production cost. Later in the 70s, leaded gasoline usage was phased out due to health hazards.
b. ***Methyl Tertiary Butyl Ether (MTBE)***: During the 90s, MTBE was used as an octane source. However, later, MTBE was phased out due to the threat of groundwater contamination.
c. ***Benzene, Toluene, Ethylbenzene, and Xylene (BTEX)***: The BTEX (known as gasoline aromatics) complex is a hydrocarbon mixture of benzene, toluene, xylene, and ethylbenzene. Although some volume of BTEX is native to gasoline, it is also added to finished gasoline to boost its octane rating. The total volume of

BTEX in finished gasoline depends on the desired octane value and other desired fuel properties.

d. ***Ethanol***: Ethanol is a good choice as an octane provider. It is also an excellent option for reducing greenhouse gas emissions, and it can also be used as a sub-octane gas.

### 2.1.3 Diesel

Diesel is typically made from crude oil after the more volatile components used in gasoline have been removed. It is often less expensive than gasoline since it requires less refining and has a considerably higher ignition point. The fuel in diesel engines is ignited by the heat of compressed air in the cylinder, rather than by a spark like gasoline engines, with the fuel injected as a spray into the hot compressed air. Diesel is available in a variety of grades, including "light-middle" and "middle" distillates for high-speed engines with frequent and wide fluctuations in load and speed (such as trucks and vehicles) and "heavy" distillates for low- and medium-speed engines with constant loads and speeds (such as stationary engines). The cetane number (a measure of igniting ease), the ease of volatilization, and the sulphur concentration are all performance requirements. The highest grades are the most volatile for vehicle and truck engines, while the lowest grades are the least volatile, leave the most carbon residue, and have the highest sulphur content. Sulphur is a significant pollutant in diesel and has been heavily regulated. Sulphur levels in traditional "normal" diesel were as high as 5000 parts per million (ppm) by weight. "Low sulphur" grades with up to 500 ppm sulphur were introduced in the 1990s, while "ultra-low sulphur" (ULSD) grades with a maximum of 15 ppm were made standard in the 2000s. There are also "zero-sulphur" or "sulphur-free" diesel with a sulphur content of less than ten ppm. Lower sulphur content decreases sulphur compounds linked to acid rain emissions and allowed diesel vehicles to be equipped with highly effective emission-control systems that greater sulphur concentrations would otherwise harm.

## 2.2 *Natural Gas*

Methane and ethane make up natural gas, which is a gaseous hydrocarbon. It has intense flammability and is colourless. Between 6000 and 2000 BCE, Iran was the first country to use natural gas seeps. Natural gas was employed for "eternal fire" by the ancient fire worshipping Persian community. Some reports claim that Chinese people used gas to dry the rock salt. At the beginning of 1790, the primary fuel for lighting streets and houses in Europe was gas generated from carbonized coal, also known as town gas (Curley, 2011).

Carbon dioxide and water are produced because of natural gas combustion. Soot, carbon monoxide, and nitrogen oxides are relatively absent from gas combustion compared to other fossil fuels. Sulphur dioxide emissions, another major air pollutant, are virtually non-existent. As a result, natural gas is the most eco-friendly option.

## *2.3 Coal*

With the discovery of fire, human civilization embarked on a new path of progress. Initially, dried straw and mostly wood were used as fuel. According to some reports, the Chinese were the first to exploit coal economically. Despite the lack of a palaeobotanical record, the coal from the Fushun mine in north-eastern China could have been used for copper smelting as early as 1000 BCE. During China's Han era, stones were frequently employed as fuel. Reiner of Liege, a European monk, was the first to report on the black ground that resembled charcoal. According to many studies, coal mining has been used in Scotland, England, and the European continent's history. Coke, made from coal, was first used in blast furnaces and forges by Abraham Darby of England in the eighteenth century. Later, James Watt's coal-burning engine ushered in a new era of ever-increasing coal demand. Continuous industrial progress and revolution have resulted in an inexhaustible demand for coal as a fuel, growing exponentially day by day.

Coal was first used to generate power for home and industrial applications in the 1880s. By 1961, coal had surpassed oil as the most used fuel for electrical generation in the USA. Coal is one of the India's most plentiful and essential fossil fuels. India is currently the world's second-largest coal production, trailing only China. India's coal reserves are estimated to be at 344.02 billion tonnes, with total lignite reserves estimated to be over 46.02 billion tonnes, according to research (Government of India Ministry of Coal "Technology Roadmap for Coal Sector", Available). Continuous economic expansion, population growth, and, most crucially, the development of daily life standards all contribute to rising energy consumption. Although ultra-supercritical PC is now in commercial usage due to its high fuel efficiency, oxyfuel is in development due to its high $CO_2$ absorption capability. The future goal of coal consumption is high fuel efficiency and cost-effective reduction of $CO_2$ and other emissions.

The use of fossil fuels is one of the significant contributors to global warming. Carbon is the most abundant element in fossil fuels. Other hazardous substances in oil have been shown to cause cancer in people when they are burned or inhaled in the form of vapours. When coal is used to create power or oil is burned as gasoline or diesel fuel for transportation, carbon is released into the atmosphere in $CO_2$. Today's principal energy sources for fuel, electricity, heating, and air conditioning are fossil fuels. Fossil fuel combustion accounts for about 86% of worldwide energy use. While fossil fuels have long been plentiful and convenient, they have also played a substantial role in climate change and global warming. The burning of fossil fuels is the primary source of greenhouse gas emissions. Each year, the combustion of fossil fuels contributes more $CO_2$ to the atmosphere. Humans can, however, take actions to reduce such impacts. Limited fuel use is the most effective technique for mitigating global warming's negative consequences because everyone uses energy sources regularly. Hydroelectric power, solar power, hydrogen engines, and biofuel are examples of non-fossil fuel energy sources that can reduce greenhouse gas emissions in the environment.

# 3 Biofuels

Given the facts mentioned above, biofuels have significant advantages over fossil fuels; hence, they can function as the alternative viable fuel source for now and future. Biofuels have been produced for several decades. Now, the popularity of biofuel has reached a significant level as global warming is alarming. The following are some of the advantages of biofuels over fossil fuels (Stančin et al., 2020):

- **Hazardous Pollution Reduction**: One of the most significant criticisms of fossil fuels is that they emit hazardous pollutants. As a result, there is global warming. Biofuels produce fewer damaging pollutants since they emit less carbon than conventional fuels.
- **Renewable, Biodegradable, and Safer Option**: Biofuel originated from organic sources, including organic waste, is renewable and biodegradable and may be produced in unlimited quantities virtually. Another important point is that the spills from biofuel can break down naturally, and these spills are non-toxic compared to oil spills. We can grow it ourselves by cultivating corn, the most widely used biofuel ingredient today. It will decompose naturally and has a low environmental impact.

***A Brief Idea on Several Generations of Biofuel*** The biofuels can be categorized into four generations based on feedstock and techniques utilized (Khan et al., 2021).

## *3.1 First-Generation Biofuel*

This group includes bioethanol, biodiesel, biogas, and all of these have marked commercial applications. Biodiesel is a substitute for diesel generated by the oil transesterification of leftover fats and oils. Several studies suggested that opting for biofuels may increase greenhouse gas emission rate. First-generation biofuel such as ethanol production requires a high amount of maize, and in addition to this, a high amount of water ranging from 5 to 2138 L (L) per 1 L of ethanol is also an immediate prerequisite for such production. This may result in the appearance of drought conditions in that agricultural area. Water resources and different wetlands will be at high risk of severe dryness due to rapid water uptake. Rapid production of biofuel may raise many social issues, such as citizens in Tanzania, Ghana, Zambia, and Kenya informed that they have lost access to their shared land because of extensive jatropha cultivation. So, there are many pros and cons for utilizing 1G biofuels for humanity

(Agoramoorthy et al., 2009; Chaudhary & Brooks, 2018; Friends of the Earth, 2010; De Fraiture et al., 2008; Implications of Biofuels on water Resources, n.d.; Measuring Corn ethanol's Thirst for Water|MIT Technology Review, n.d.; Senauer, 2008;).

## 3.2 Second-Generation Biofuel Manufacturing Includes Bioethanol Formation from Crops and Biodiesel Synthesis from Fat, Lignocellulosic Biomass Formation, and Waste Vegetable Extraction

It involves the processing of crop and forestry residues, which hampers the normal bacteriological and physical properties of soils. It is reported that when the deadwood from the forest is removed, it eventually decreases the variability of bird species drastically. Although 2G biofuels are cost effective, many technological challenges and constraints need to be overcome fast (Viikari et al., 2007; Levidow & Carr, 2009; Mohr & Raman, 2015; Havlík et al., 2011; Powlson et al., 2008; Riffell et al., 2011; Victorsson & Jonsell, 2013; Kazi et al., 2010; Zhu & Pan, 2010; Yamakawa et al., 2018).

## 3.3 Third-Generation Biofuel

Third-generation biofuel includes microalgae and macroalgae. Algae is a potential source of third-generation biofuel because it can reduce carbon dioxide emissions as compared to the application of fossil fuels (Khan et al., 2021).

## 3.4 Fourth-Generation Biofuel

This is the most promising group of biofuels, which includes the use of genetically engineered microalgae, yeast, cyanobacteria, etc. Among different microalgal species, those with high photosynthetic efficiency, low susceptibility to disease, and more lipid content are triggered for further cultivation. The genetically modified algal biomass is treated by different processes, such as anaerobic digestion giving methane, hydrogen; fermentation giving bioethanol; transesterification results into biodiesel and gasification giving syngas. Although this group of biofuel has lots of benefits, still it has negative impacts too. The mass release of genetically engineered microalgae can induce future environmental challenges like lateral gene transfer, toxicity, ecological changes, etc. (Corportation; DuPont closes Iowa cellulosic ethanol plant; Versalis Wins Bid to Acquire Four Mossi and Ghisolfi Group Companies|Bioenergy International, n.d.; Snow & Smith, 2012).

## 4 Discussion

Alternative fuels are unavoidable if a sustainable ecology is to survive. For the swift and efficient decarbonization of the transportation and industrial sectors, the choice of biofuel sources is becoming increasingly important. Since every country has no vast sources of conventional fuel, it must import petroleum, coal, and natural gas from other countries. This import is a significant economic burden for such countries, and it is one of the primary reasons for choosing biofuel as an alternative fuel source. Furthermore, when compared to conventional fuel, the use of biofuel is less expensive. The biofuel industry may create more jobs and, without a doubt, strengthen the nation's economy. Biofuels are less detrimental to the environment because they are derived from renewable resources.

Furthermore, compared to conventional fuel, these generate significantly less carbon dioxide and other harmful pollutants. It has also been discovered that burning biofuel for an extended period reduces PM levels in the air. Carbon dioxide, which plants in photosynthesis need, is produced as a direct product of biofuel combustion (to a limited extent). As a result, the process is self-sustaining. Switching to biofuel is unquestionably becoming excessively expensive because the entire world has been acclimatized to the use of regular gasoline. Its production expenses are excessively high. A monoculture technique is essential since biofuels are made from plants (such as maize). Monoculture can deplete soil fertility while also amplifying insect infestations. Fertilizers boost plant growth since biofuel takes many plant resources. These fertilizers have various detrimental effects on soil, water, and human health. As biofuels are created from sugar-containing plants like fruits and vegetables, relying solely on sugar-producing crops for fuel could lead to a rise in global hunger. Biofuel production's downsides include changes in land-use patterns, water scarcity in agricultural areas, and significant industrial pollution. Burning biofuels produces carbon dioxide (albeit small), but it still contributes to global warming mitigation. Biofuels are not suitable for cold areas since they absorb more moisture than fossil diesel. It also encourages microbial growth in car engines, which clogs engine filters.

Although biofuel has several disadvantages, it is expected that with advancements in technology, exclusive research, and development, third- and fourth-generation biofuel will become a viable alternative fuel for commercial use. One day biofuels can be one of the safer nature-inspired options that could be genuinely implemented as a transitional strategy if the prerequisites related to sustainability issues are met appropriately.

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# Developmental Perspectives of the Biofuel-Based Economy

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## 1 Introduction

### *1.1 Substituting Fossil Fuels to Reverse Climate Change*

Currently, there is a high dependence on fossil resources to produce energy and raw materials. Oil derivatives continue to be the primary source of energy consumption worldwide, representing 31% of the energy consumed, followed by coal with 26% and gas with 23% in 2019. According to current data, there is still many unexploited fossil energies. In the case of oil, specifically, there are 1,700,803.80 million barrels (Eurostat, 2020; International Bank for Reconstruction and Development, 2020; National Center for Information on Hydrocarbons (CNIH), 2020; Víctor, 2013). However, the current consumption rate is untenable in the long term. In recent centuries, a large amount of fossil fuels has been extracted and used, approximately 80%, 50% and 30% of the total existing coal, gas and oil reserves, respectively. Besides this, a climatic emergency is pushing alternative energy sources in transport, heating and industry. These reserves must remain underground to reduce greenhouse emissions; otherwise, the combustion of oil, natural gas and carbon would increase the global

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mean temperature by more than 2 °C (Pellegrini et al., 2021). Carbon dioxide ($CO_2$), nitrous oxide ($NO_2$), ozone ($O_3$) and methane ($CH_4$) can emit and absorb infrared radiation, ensuring a mild temperature in the atmosphere. Expansion of industry, transport and agriculture based on fossil fuels has increased the levels of these gases in the atmosphere (Hu et al., 2021).

Consequently, there is an unwanted increase in the average temperature. By transforming the energy sector towards a renewable perspective based on the substitution of petroleum derivatives, environmental, social and economic benefits will be achieved. The main renewable sources that allow this transformation are biomass, solar energy, wind energy and biofuels such as bioethanol, biodiesel, biomethane and biobutanol (Bertheau, 2020). In the case of biomass and biofuel, renewable feedstock must be utilized to ensure sustainability, for instance, agricultural and forestry wastes.

## *1.2 Biofuels and the Circular Economy*

The world's population by 2050 will reach 9 billion inhabitants according to the most recent forecast (United Nations, 2021), which means a concomitant increase in the demand for food and feed and a subsequent increase in waste production. The transformation of these wastes into bioenergy has been pointed out as the solution for sustainable development. During the last decade, agricultural waste production accounted for a potential generation of 90 million tonnes of oil equivalent (MTEP), which is considerably higher than any other existing by-product, such as wood chips (57 MTEP) from municipal waste (42 MTEP). The waste generated in agricultural and livestock activities has been on the rise in recent. If agricultural wastes are insufficiently managed, environmental problems arise as a cause of soil and water pollution or indirect greenhouse gas emissions (GHG). In this scenario, waste can be considered a helpful resource to generate energy and high-value products. The conversion of agricultural, livestock and forestry residues into bioenergy is currently used to reduce consumption and dependence on fossil fuels. Increasing the transformation of waste materials into bioenergy is a crucial process for sustainable development during the next decades. Agricultural residues present advantages over other residues (such as urban wastes) due to their inherent features: homogeneous chemical composition, well-known processing techniques and ubiquity production. The use of wastes as an energy source to produce biofuels and the obtaining of high-value chemical compounds can be a great step for the proper development of the circular economy (Song et al., 2020).

### 1.3 Energy Demand

Concurrently to the population growth, expansion of cities and towns has increased the energy consumption, accounting for around 30% of world energy consumption with an increasing trend. Energy consumption in 2019, by the residential and commercial sector, in the USA was approximately 6.24 million megawatts hour (MWh), which is equivalent to 28% of end-use energy consumption (Dong et al., 2021). Nowadays, most of the buildings present low and medium energy efficiency. Therefore, there is a large scope for improvement (Luo et al., 2021).

The transport sector represents more than a quarter of the total energy consumed worldwide, 26% (Sandoval-García et al., 2021). In the USA, only 5% of energy is used in biofuels. The rest comes from fossil sources, with gasoline being the most used fuel, 56%. The deployment of electric vehicles has grown rapidly in the last decade, with 10 million vehicles in use by the end of 2020. China has the most electric vehicles in stock, 5.4 million, followed by Europe with 3.3 million and the USA, which has 1.8 million. Worldwide, it has gone from having zero electric vehicles to having 11.3 million in stock (International Agency for Energy, 2021).

Regarding GHG emissions, the electric vehicle is not neutral since an important amount of the electricity to recharge the batteries currently could involve utilizing fossil sources. In this scenario, it is necessary to opt for alternative energy sources such as biofuels (Neves et al., 2017).

Countries with emerging economies are at the centre of concern, as they have experienced rapid economic growth and high energy use and are deeply affected by economic globalization. As the world's largest developing and growing economy, China accounted for 24% of global energy consumption and 34% of global energy consumption growth in 2018 (Acheampong et al., 2021).

In 2019, in the EU-27, energy derived from renewable sources accounted for 19.7% of the energy consumed, just 0.3% below the 2020 target of 20%. In the USA, energy production from renewable sources accounted for about 12% of total energy production (Lahiani et al., 2021). Governments have numerous incentives to promote the implementation of energy efficiency since this generates economic, social and environmental benefits (American Council for an Energy-Efficient Economy, 2019) (see Sect. 4).

### 1.4 Current Situation of Biofuels

To achieve the United Nations (U.N.) Sustainable Development Goals (SDGs), efforts must be focused on increasing electricity production from renewable sources and heat and fuels from residual biomass. This fact is the focus of various global development initiatives. At present, electrical energy comes from the following sources with their respective installed power 142 GW for photovoltaic solar energy, 80 GW for wind energy, 32 GW for hydroelectric energy and 12 GW for other renewable energies, according to data from the International Agency for Energy (IEA, 2021). Electricity production through renewable sources such as solar or wind generates great intermittence and uncertainty when adjusting the supply with the energy demand since they depend greatly on meteorology and seasonality. Therefore, it is necessary to opt for other renewable energy sources that ensure a continuous energy supply, especially in the heavy transport sector and heat supply (Abedinia et al., 2019).

Regarding raw materials to produce biofuels, there is a positive trend towards using agricultural wastes, such as biological and municipal waste and sewage sludge (Zhu et al., 2021), to the detriment of the use of grain generated in energy crops. The traditional sources for producing biofuels come from energy crops (sugarcane, beet and oleaginous seeds). These materials compete with the cultivated areas for food and feed production; in addition, pollution due to chemical fertilizers and large consumption of water endangers sustainability in the long term. By using the residues (such as straw), which are generated from the crops destined for food, to obtain biofuels, the contamination risks are reduced, and GHG emissions of the food production process are reduced. This trend is expected to continue since, in this way, energy generation does not conflict with the food sector (Yu et al., 2022). According to the report prepared by the Renewable Energy Association, the supply and demand for biofuels have increased in the last 20 years, especially the production of bioethanol, which grew by around 1000% between 2000 and 2020.

Regarding the development of systems to produce biomethane, in recent years, Europe has seen a significant increase in the production of this biofuel with an average annual rate of 20% (European Biogas Association, 2020). In recent years, new techniques for biogas improvement such as Cryobox-Bio are being developed in which biogas polishing and liquefaction processes (Bio-LNG) are integrated, which provides a methane recovery rate higher than 99%, and low-cost photosynthetic upgrading techniques with biomethane yields of more than 95%. Both technologies provide clean biomethane suitable for transportation, power generation and the energy industry (Rodero et al., 2019).

Biofuels produced from agricultural residues can provide energy products compatible with the current energy infrastructure (Kurczyński et al., 2021; Millo et al., 2021). Biofuels can be used in transportation, industry and heating in pure form or mixed with fossil derivatives. Therefore, the introduction of biofuels provides a transition for energy sustainability in the transport, industrial and construction sectors. By using biofuels, air pollution and GHG emissions are reduced. These biofuels are considered $CO_2$-neutral since the carbon embodied comes from atmospheric carbon dioxide previously fixed from biomass.

Furthermore, biofuels have a greater capacity to reduce greenhouse gas emissions during the life cycle than electricity (Andersson & Börjesson, 2021). Therefore, replacing fossil fuels with biofuels makes it possible to reduce global warming (Scovronick & Wilkinson, 2013). However, it is necessary to combine electrical energy from renewable sources with the use of biofuels.

According to data from the International Energy Agency (IEA) 2013, oil consumption will decrease relative to its global market share by at least 5% by 2040.

This reduction will be based on a continuous substitution by renewable electricity and energy products. Liquid biofuels, such as bioethanol and biodiesel, are more frequently used to replace fossil fuels in the transportation sector. These biofuels are essential to mitigate climate change, revitalize agricultural economies and achieve a secure energy supply with low $CO_2$ emissions (Løkke et al., 2021a). The production and consumption of biofuels have increased worldwide mainly due to their use in the transport sector.

## 1.5 World Crop Stubble Situation

The most widespread crops are cereals, rice and corn, which are mainly produced for feed and food, and generate a final residue of a lignocellulosic nature. Although a considerable amount of this waste is consumed in traditional uses, large volumes were left unused. Lignocellulosic biomass refers to cereal straw made up mainly of cellulose, hemicellulose and lignin, representing 90% of its dry weight, excluding the biomass of the cereal grain, which is mainly made up of proteins and sugars. Lignocellulosic biomass is the most abundant organic matter on earth, which has the advantage of being biodegradable and renewable. The world production of these staple crops grows simultaneously as the world population (see Fig. 1). Sugarcane is the most productive crop among staples, accounting for almost 2000 million tonnes of raw material per year. Cereal production is around 2800 million tonnes, according to the latest report from the Food and Agricultural Organization (FAO) of the U.N. Regarding the wheat, its production is close to 800 million tonnes.

Regarding rice, current production is above 500 million tonnes. As for the corn, production is around 1200 million tonnes. The USA stands out as the main producer

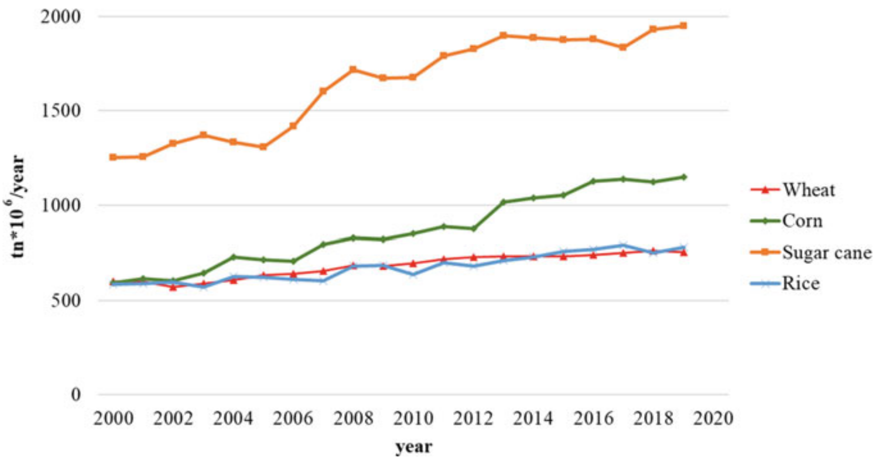


**Fig. 1** Evolution in crop production

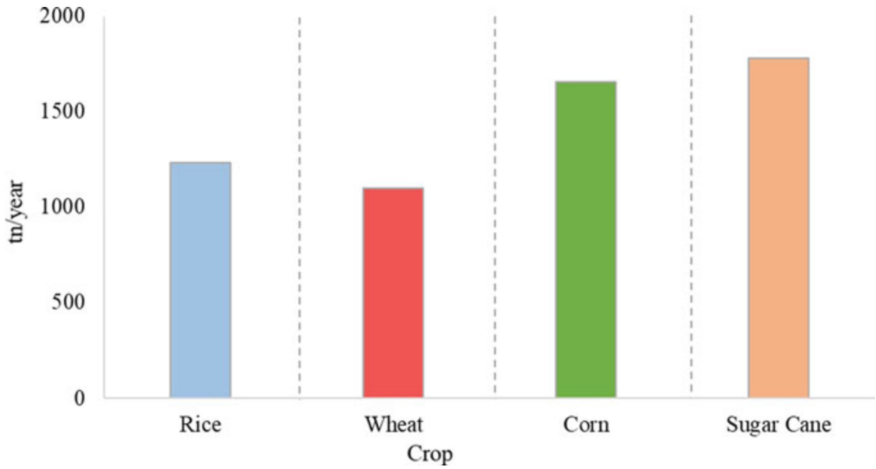


**Fig. 2** Global stubble production of the main crops

of this crop. America is a continent with a large corn producing capacity; it produces more than 50% of the world's corn.

The amount of stubble produced by a crop is highly variable and depends on the type of soil, climate, cultivation techniques and technologies, etc. Production fluctuates depending on the agroecological areas. The straw produced can be calculated based on its harvest index (H.I.) (Eqs. 1 and 2). This index is obtained from the relationship between the grain's weight and the plant's total weight at maturity without considering the roots. This index may vary according to the crop's area, variety, and management.

$$\text{Harvest index (HI)} = \frac{\text{Grain weight (GW)}}{\text{Total plant weight except roots (PW)}} \tag{1}$$

The following relationship was used for the calculation:

$$\text{Straw production} = \frac{\text{Grain production } (t/\text{Ha})}{\text{HI}} \Delta(1 - \text{HI}) \tag{2}$$

The amount of stubble generated estimation per surface must be considered for the management planning and potential of the by-product (see Fig. 2).

## 2 Biofuels from Lignocellulosic Materials

The generation of biofuels from lignocellulosic materials, composed of cellulose, hemicellulose, and lignin, is of great interest due to its low cost and high availability.

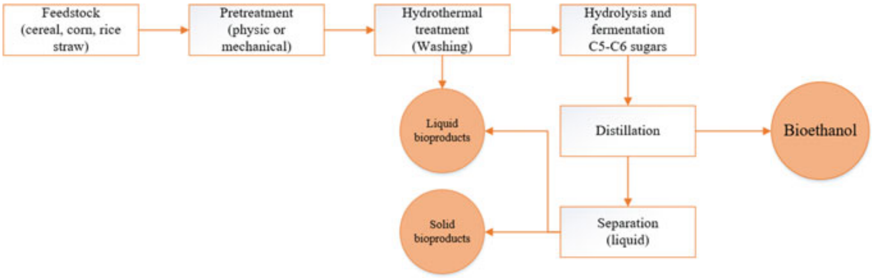


**Fig. 3** Bioethanol process flow diagram

Thus, nowadays, different physicochemical and biological methods allow the use of the sugars that make up cellulose and hemicellulose and their transformation into biofuels such as biomethane, bioethanol or biobutanol. The biorefinery integrates the conversion processes of lignocellulosic biomass into biofuels, energy and chemical products, being of great interest as an alternative to fossil resources resulting in an economic and environmental positive impact.

## 2.1 Bioethanol

As can be seen in Fig. 3, after a first physical or mechanical pretreatment that seeks to reduce the particle size, a hydrolysis process is associated to reduce the crystallinity of the cellulose, the dissociation of the lignin–cellulose complex and the increased surface area to promote degradability by fermenting microorganisms.

Subsequently, sugars, acetic acid, furan derivatives, phenolic derivatives and various sugars can be found in the generated solution. On the latter, microorganisms selected for a specific molecule carry out fermentation of the sugars found (e.g. *S. cerevisiae* with the glucose molecule). In the last part of the process, distillation is carried out, in which the components or substances of the liquid mixture are separated with selective boiling and condensation. Bioethanol comes out of this last phase for its final use as a biofuel (Ingrao et al., 2021; Sarkar et al., 2012).

## 2.2 Biomethane

The production of biomethane is based on anaerobic digestion, a biological process in the absence of oxygen. Biogas is generated with a significant amount of biomethane, and another part of carbon dioxide and sulfuric acid based on bacterial activity. These last two are subsequently eliminated by upgrading, obtaining biomethane in 90–99% of the total volume.

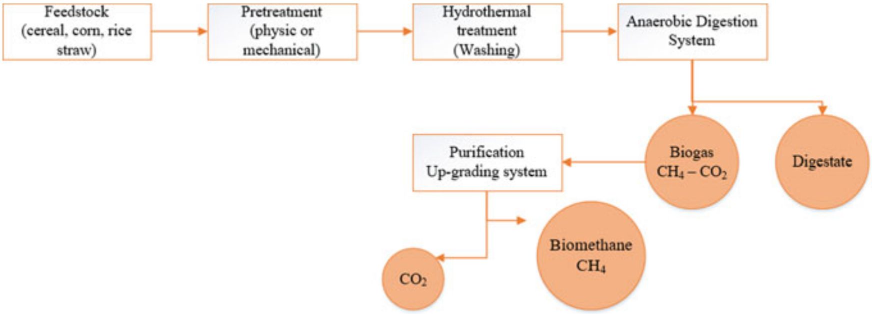


**Fig. 4** Biomethane process flow diagram

In the process, there is a first pretreatment phase where hydrolysis accelerates the obtaining of monosaccharides, amino acids, and long-chain fatty acids. Subsequently, in the medium generated with the substrate mixture with bacterial inoculum, the hydrolysis and acidogenesis phase takes place where $H_2$, $CO_2$, acetic acid and other short-chain fatty acids are obtained as by-products. The acetate at this point, under the action of methanogenic archaea, forms methane, $CO_2$ and $H_2S$; these last two compounds decrease the calorific power of the biogas and prevent its use as biofuel in vehicles (Prussi et al., 2019). Different technologies can be used for its elimination, such as pressure water washing, chemical washing, PSA adsorption systems, membrane separation, organic solvent washing, cryogenic separation and biogas photosynthetic enhancement technology with microalgae (Rodero et al., 2019).

In the anaerobic digestion process, a liquid organic waste called digestate is also generated as bio compost. A diagram of this simplified process is shown in Fig. 4.

## 2.3 *Biobutanol*

In this process, an ABE fermentation (acetone–butanol–ethanol fermentation) occurs, characterized by bacterial activity to produce acetone, n-butanol and ethanol from carbohydrates embodied in the lignocellulosic biomass.

Two different stages are present in the ABE fermentation: acidogenesis, where there is rapid cell growth, and bacteria produce acetic acid, butyric acid, and $CO_2$ and from sugars generated in the previous phase; and a second phase, solventogenesis, where cell growth reaches a stationary phase, and organic acids are assimilated again, producing the ABE products: acetone, butanol and ethanol in the usual ratio of 3:6:1. (Niemisto, 2013; Liu et al., 2011; Xiros, 2017). The products of this fermentation are generally acetone, butanol, ethanol, acetic acid, butyric acid, hydrogen and carbon dioxide (Meramo, 2020; Jones & Wood, 1986; Ranjan, & Moholkar, 2012) (see Fig. 5).

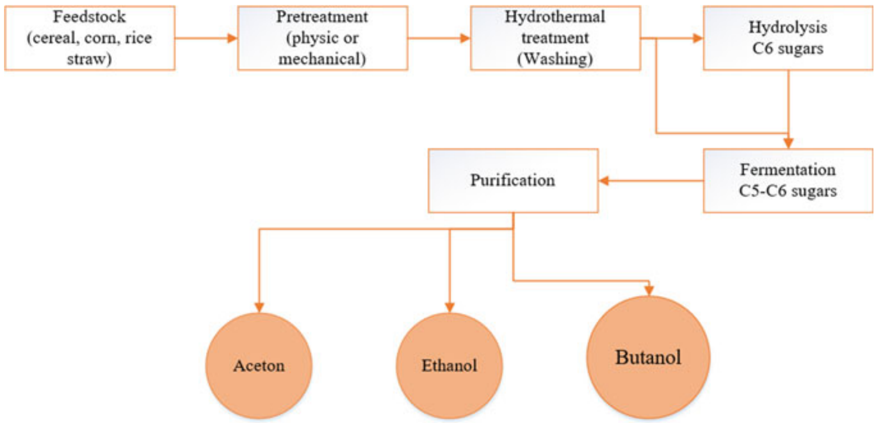


**Fig. 5** Biobutanol process flow diagram

## 2.4 *Pretreatments*

Lignocellulose has low solubility in water and is very resistant to decomposition, which difficult the use of the monosaccharides. This fact has led to the research of chemical and biological methods that accelerate the hydrolysis of lignocellulose and the accessibility of these sugars Kim et al., (2016). The methods require a large amount of water and reagents (strong acids or bases), as well as high-temperature conditions. In contrast, biological methods do not require reagents or large amounts of water and can be carried out at room or slightly higher temperatures. The enzymatic hydrolysis processes are biological methods widely used at the industrial level. Pretreatments allow cellulose hydrolysis yields to increase from less than 20% of theoretical yields to values greater than 90% and are essential for better energy use (Lynd, 1996). Lignocellulosic materials are attractive due to their high availability in various climates and locations, which is why there are currently physicochemical and biological methods for its transformation into value-added products such as biofuels (e.g. biogas or bioethanol).

There are many techniques commercially available for substrate pretreatment. It depends mainly on the type of substrate. The most common treatments are thermal, chemical, physical/mechanical, ultrasonic, microwave, biological and metal addition methods. For the lignocellulosic raw material (wheat, corn and rice stubble), the most effective techniques resulting in considerable increases in biomethane production are depicted in Fig. 6 (Chandra et al., 2012; Fu et al., 2015; Gallegos et al., 2017; Hjorth et al., 2011; Kainthola et al., 2019; Kong et al., 2018; Mancini et al., 2016; Patil et al., 2016; Schroyen et al., 2014; Sharma et al., 1988; Song et al., 2014; Wyman et al., 2018).

During the last years, there have been many studies related to the hybridization of more than one pretreatment, and it has been observed that the processes optimize the

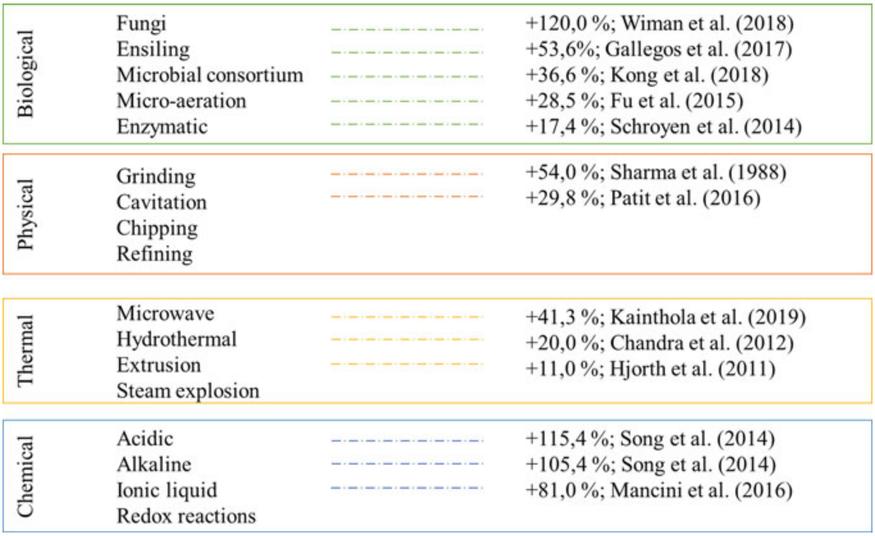


**Fig. 6** Classification of pretreatments for lignocellulosic material

use of chemicals and energy. In addition, it has been reported that methane production improvement combines pretreatments.

## 3 Case Study

The potential energy production in biofuel was calculated considering 1 $m^3$ of common agricultural wastes: cereal straw, rice and corn stubble. These substrates were evaluated as feedstock for biomethane production through anaerobic digestion and bioethanol or biobutanol through alcoholic and ABE fermentation, respectively. An economic estimation from the potential energy generated (kWh) or distance (km) covered in the case of each substrate and type of biofuel is presented.

The methodology for the study is based on three phases for the final economic evaluation in each biofuel production process (see Fig. 7). The first phase consists of calculating the potential of each substrate, taking into account the chemical composition and physical features as well as the transformations required. The second phase consists of estimating energy output and input, respectively. According to previous studies, energy consumption was estimated based on the parameter Energy Return on Investment (EROI). In the third phase, there is an energy balance that is used for economic quantification.


**Fig. 7** Methodology for the study case proposed

## *3.1 Characterization of Substrates*

Each substrate's physical and chemical characteristics are quite similar, although slight variations are possible depending on weather, density or hemicellulose, cellulose lignin and ash content. This fact could be reflected in the result (Wiselogel et al., (1996). Average values have been considered for each case since these parameters depend largely on numerous environmental factors such as humidity, temperature and light. Table 1 shows a reference value for the main parameters.

The density and humidity data of the studied substrates, as well as the chemical composition data of the substrates, have been obtained from the following references: (Emami et al., 2014; Lawther et al., 1996; Saad, 2012) for cereal straw; (Ishii & Furuichi, 2014; Zhang et al., 2013) for rice straw; and (Viamajala et al., 2007) for corn stubble.

The density of each residue is slightly different; the average value for cereal straw is 0.17 kg / l, rice straw is 0.15 kg/l, and corn straw is 0.13 kg/l. The residue with the highest cellulose content is cereal straw 60.16 kg/m$^3$, followed by rice straw 51.52 kg/m$^3$ and finally corn straw 43.82 kg/m$^3$. The hemicellulose content is similar between cereal straw and corn with 45.12 kg/m$^3$ and 45.26 kg/m$^3$, respectively, rice straw is lower with 39.74 kg/m$^3$. Considering the difference between crops, it can be observed that the data are quite similar since there are no significant variations

**Table 1** Characterization of substrates

| | Cereal straw | Rice straw | Corn straw |
|---|---|---|---|
| Volume | 1 m$^3$ | 1 m$^3$ | 1 m$^3$ |
| Straw density | 0.17 kg/L | 0.15 kg/L | 0.13 kg/L |
| Mass | 170 kg | 150 kg | 130 kg |
| Humidity | 6% | 8% | 18% |
| Cellulose content | 60.16 kg | 51.52 kg | 43.82 kg |
| Hemicellulose content | 45.12 kg | 39.74 kg | 45.26 kg |
| Lignin content | 31.58 kg | 33.12 kg | 6.96 kg |

in chemical composition, except with corn stubble, which contains a lower cellulose value, which ultimately results in less bioenergy production.

## 3.2 Transformation of Cellulose and Hemicellulose in Final Bioenergy Products.

Once the content of transformable organic materials was estimated, the potential production of biofuel was calculated. Previously reported studies have been taken as a reference in which the processes were analysed considering the net energy production. As presented in the work of Hall et al. (2011), who studied the processes for obtaining biofuels using the parameter EROI, the result could differ depending on the processes chosen for biofuels production. In the present work, lignocellulosic substrates have been considered a secondary by-product within the main agricultural activity, and therefore, consumption involved in grain (food) production has been considered zero, following the approach described by Kim and Dale, (2005). For the biofuel production process calculations, the following stoichiometric equations have been considered (Deublein & Steinhauser, 2008).

Hemicellulose is transformed into xylose, glucose and other sugars after pretreatment:

$$\text{Hemicellulose} \rightarrow (C_5H_{10}O_5)+(C_6H_{12}O_6) + \text{other sugars} \tag{3}$$

Cellulose after the hydrolytic action of endoglucanases, cellobiohydrolases and glucosidases is transformed to glucose

$$(C_6H_{10}O_5)\ 2n \rightarrow n(C_{12}H_{22}O_{11}) \rightarrow 2n(C_6H_{12}O_6) \tag{4}$$

These products are the precursors of ethanol after fermentation and distillation:

$$3(C_5H_{10}O_5) \rightarrow 5(C_2H_5OH) + 5CO_2 \tag{5}$$

$$(C_6H_{12}O_6) \rightarrow 2(C_2H_5OH) + 2\ CO_2 \tag{6}$$

In the case of ABE fermentation, the following transformations take place:

$$(C_6H_{12}O_6) \rightarrow (CH_3COCH_3)(\text{Acetone}) + 3\ CO_2 + 4\ H_2 \tag{7}$$

$$(C_6H_{12}O_6) \rightarrow (C_4H_9OH)(\text{Butanol}) + 2\ CO_2 + H_2O \tag{8}$$

$$(C_6H_{12}O_6)\text{®}2(C_2H_5OH)(\text{Ethanol}) + 2\ CO_2 \tag{9}$$

For biomethane obtention, there are reactions different because the process is based on anaerobic digestion. We have the following transformations:

$$(C_6H_{12}O_6)\ n \rightarrow 3n\ (CH_4)(\text{biomethane}) + 3n\ (CO_2) \tag{10}$$

### 3.3 Energy Produced and Economic Revenues

The energy balance and economic evaluation were based on different EROI studies in which energy involved in the whole process was considered. This reflects the energy contained in the form of biofuel considering the raw material (in this case, cereal, corn and rice stubble) and the amount of energy that is necessary to transform this resource. An energy analysis has been carried out for each biofuel and each waste substrate chosen to obtain it.

There are large differences between previous works published in this matter, which leads to large differences in the calculated rates of return.

As previously explained, the consumption of the agricultural production process is excluded from energy balances, including the fuel consumed, machinery, electricity, fertilizers, irrigation, herbicides, seeds and various transports. Therefore, the collection of stubble in the field is regarded as starting point of the process.

In the input part, the theoretical potential has been considered a function of the density of the material, the humidity and the average content of cellulose, hemicellulose and lignin in percentage terms and their conversion rates to glucose after hydrolysis. Considering the inputs, the following results have been obtained taking 1 $m^3$ of the substrate as a common base point for each process (Table 2).

The table shows the final amount of net energy obtained in the three processes to obtain each of the biofuels studied, starting from 1 $m^3$ of the substrate, considering the energy generated as biofuel and the energy consumed in the production process.

In obtaining bioethanol, it produces more energy from cereal straw, obtaining 224.10 kWh; secondly, there is 206.15 kWh rice straw and 151.87 kWh corn straw. In obtaining biobutanol, the highest value was obtained through rice straw 47.10 kWh, secondly, was cereal straw 44.33 kWh and finally corn straw 36.02 kWh (Sun et al., 2019). In the biomethane process, the highest amount of energy generated was obtained through corn straw 121.17 kWh, cereal straw 95.79 kWh, and the lowest value was obtained with rice straw 66.16 kWh (Gómez-Camacho et al., 2021).

Considering the energy produced with each waste, the distance travelled with each biofuel was calculated. Table 3 shows the economic data expressed in dollars that are obtained both from the sale of the net energy obtained and from the consumption in vehicles in the form of biofuel. This analysis revealed that bioethanol presents better economic performance.

The pretreatment technique continues to be the step with the highest energy consumption, as mentioned, critical for these substrates.

Figure 8 represents the net energy produced in biofuel for each waste.

**Table 2** Energy production (inputs, output, net)

| Energy (KWh) | Biomethane | | | Bioethanol | | | Biobutanol | | |
|---|---|---|---|---|---|---|---|---|---|
| | Cereal straw | Rice straw | Corn straw | Cereal straw | Rice straw | Corn straw | Cereal straw | Rice straw | Corn straw |
| Output | 304.0 | 210.0 | 384.6 | 5311 | 488.5 | 359.9 | 133.0 | 141.3 | 108.1 |
| Input | 208.3 | 143.8 | 263.4 | 307.0 | 282.4 | 208.0 | 88.7 | 94.2 | 72.0 |
| Net | 95.8 | 66.2 | 121.2 | 224.1 | 206.2 | 151.9 | 44.3 | 47.1 | 36.0 |

**Table 3** Economic quantification of energy generated and distance travelled

| | | Wheat straw | | Rice stubble | | Corn stubble | |
|---|---|---|---|---|---|---|---|
| Biomethane | Energy production (KWh) | 95.79 | kWh | 66.16 | kWh | 121.17 | kWh |
| | km (vehicle) | 162.91 | km | 112.52 | km | 206.06 | km |
| | Energy production ($) | 11.50 | $ | 7.94 | $ | 14.54 | $ |
| | km (vehicle) $ | 40.73 | $ | 28.13 | $ | 51.52 | $ |
| | | Wheat Straw | | Rice stubble | | Corn stubble | |
| Bioethanol | Energy production (KWh) | 224.10 | kWh | 206.15 | kWh | 151.87 | kWh |
| | km (vehicle) | 315.63 | km | 290.35 | km | 213.90 | km |
| | Energy production ($) | 26.89 | $ | 24.74 | $ | 18.22 | $ |
| | km (vehicle) $ | 20.78 | $ | 19.11 | $ | 14.08 | $ |
| | | Wheat Straw | | Rice stubble | | Corn stubble | |
| Biobutanol | Energy production (KWh) | 44.33 | kWh | 47.10 | kWh | 36.02 | kWh |
| | km (vehicle) | 68.31 | km | 72.58 | km | 55.50 | km |
| | Energy production ($) | 5.32 | $ | 5.65 | $ | 4.32 | $ |
| | km (vehicle) $ | 7.77 | $ | 8.26 | $ | 6.31 | $ |

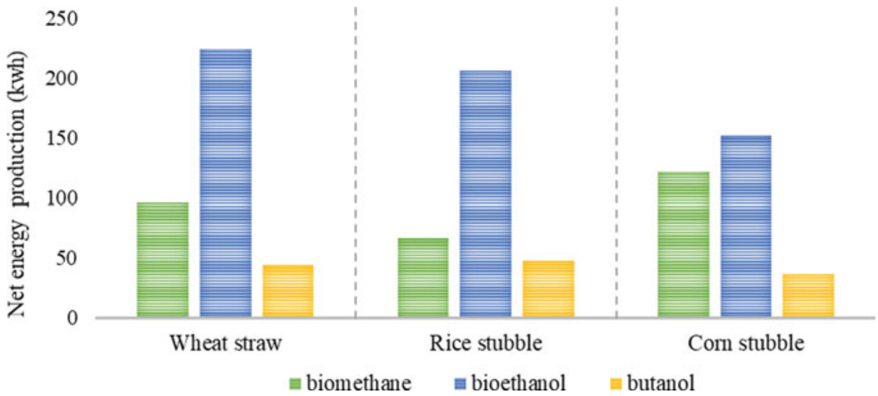


**Fig. 8** Net energy production by biofuel and from 1 $m^3$ of substrate for cereal, for rice and corn stubble

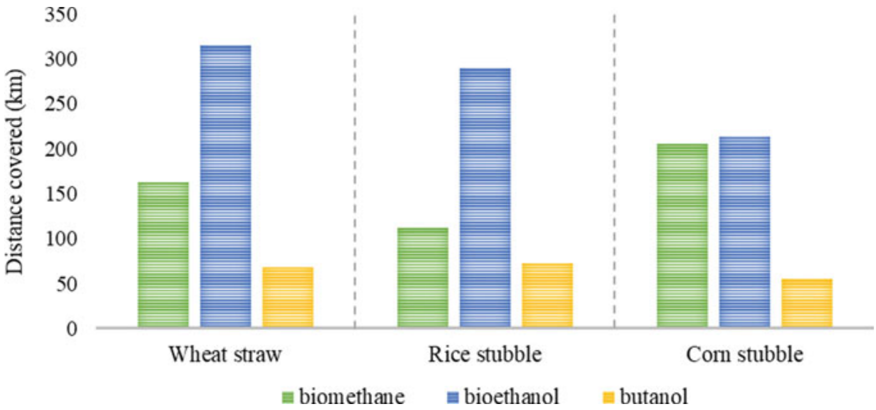


**Fig. 9** Distance covered by biofuel starting from 1 $m^3$ of substrate for cereal, for rice and corn stubble

As shown in the figure, bioethanol presented a greater energy potential in a theoretical framework. On the other side, methane showed a lower value since a significant amount of organic matter is not degraded in the process. The following Fig. 9 represents the distance in km that could be travelled with biofuels produced by waste, replacing fossil fuels.

The longest distance travelled is obtained from cereal straw transformed to bioethanol with 315.63 km, in second place, with rice straw presented a value of 290.35 km and lastly, corn straw with 213.90 km. For biomethane, the greatest distance is achieved through corn straw, 206.06 km, followed by cereal straw, 162.91 km, and lastly, rice straw with 112.52 km. Biobutanol showed the lowest yields compared to the previous biofuels, with values of 72.58 km, 68.31 km and 55.50 km, for rice straw, cereal straw and corn straw, respectively.

For the economic analysis of the use of the straw by-product through the explained processes, each case's theoretical energy input and output have been taken, considering the study presented by Leung and Wang (2016). The next graph represents the income from the sale of biofuel (Fig. 10).

Biomethane production is economically more profitable since its price is higher than other biofuels. For the calculations, the average values of the current fuel market were used, taking a value of $ 1.15 per kg of biomethane for 0.79/l bioethanol and $ 0.91/l biobutanol. Data were taken from the Alternative Fuel Prices Report, July 2021 and the U.S. Energy Information Administration (US Department of Energy, 2021). 1 $m^3$ of corn straw will provide $ 51.52 if biomethane is produced, while $ 40.73 are obtained in the case of corn straw. Lowest biomethane revenue is obtained from d from rice straw, $ 28.13. In the case of bioethanol, $ 20.78 would be obtained with cereal straw, $ 19.11 with rice straw and $ 14.08 with corn straw. In the case of biobutanol, $ 8.26 would be obtained with rice straw, $ 7.77 with cereal straw and $ 6.31 with corn straw.

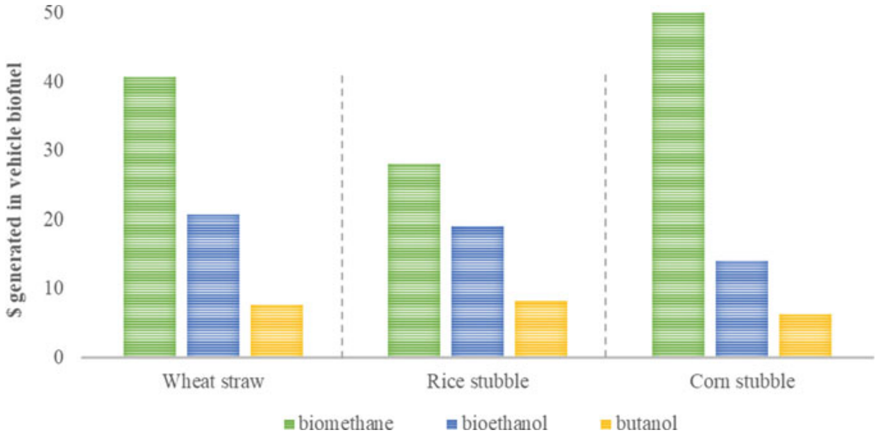


**Fig. 10** Economic benefit from biofuel generated

Considering the inputs and outputs and taking the market price of the costs associated with each process, biomethane offers a better ratio per unit volume of stubble. The process is progressing, especially in the biogas improvement part, which makes this biofuel an alternative to conventional fossil fuels. In the same way, both ethanol and butanol also provide positive balances.

Figure 11 represents the money that would be obtained from the sale of energy, considering a value of 0.12 $/kWh as the price of energy, which corresponds to the average value of the current market.

In the case of biomethane, the following values are obtained: $ 14.54, $ 11.5, $ 7.94 for corn straw, cereal and rice, respectively. In the case of bioethanol, $ 26.89, $

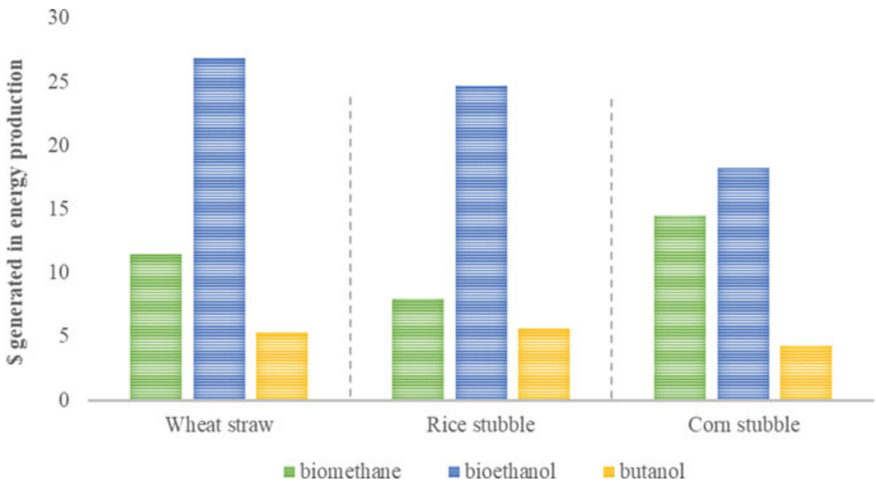


**Fig. 11** Economic benefit for generated energy

24.74, $ 18.22 are obtained with cereal straw, rice and corn, respectively. In addition, in the case of biobutanol, $ 5.65, $ 5.32 and $ 4.32 are obtained with rice straw, cereal and corn, respectively.

Although the internal combustion engines consume a large amount of bioethanol (12 L/100 km), bioethanol delivers a longer distance travelled per unit of waste processed. The biomethane and biobutanol consumptions used in the calculations are 4 kg/100 km and 8 L/100 km, respectively.

An important benefit can be obtained from 1 $m^3$ of lignocellulosic residue in each pathway used. The three biofuels studied to contribute to positive economic balances. Biomethane, used as transport biofuel, presents the highest economic benefits. However, in terms of net energy production, bioethanol exhibits better performance. This situation can be changeable since prices fluctuate according to the energy and food markets.

## 4 The Legal Framework of Bioenergy and Its Connection with the Circular Economy – The European Initiative

The integration between climate and energy is unquestionable. Biomass energy has a fundamental role in the energy transition towards a renewable model to achieve, at the same time, a decarbonized and circular economy.

This section will study bioenergy and biomass fuels have been considered in the new Renewable Energy Directive (European Parliament, 2018) and their role in this economic transition.

### *4.1 Bioenergy and Circular Economy*

The assessment impact of the Climate Objective Plan to reduce greenhouse gas emissions (GHGs) by 55%, at the same time, is necessary to reach a share of renewable energies by 2030 of between 38 and 40% [COM (2020) 562] (European Commission, 2020b). The main underlying idea is that the reduction of emissions depends on the expansion of renewable energies, which, as reflected in the Strategy for the Integration of the Energy System [COM (2020) 299 final], must be distributed geographically and flexibly integrate different energy vectors, while continuing to make efficient use of resources and avoiding pollution. The link between bioenergy and circular economy is related to the fact that the circular economy represents an alternative compared to a linear economy (extract-manufacture-use-throw away), consisting of keeping resources in use for as long as possible reducing and delaying the generation of waste. This was enshrined in the Commission Communication of 2 December 2015, under the title "Closing the circle: an E.U. action plan for the circular economy"

[COM (2015) 614 final] (European Commission, 2015), and it emerges with intensity through the European Green Pact that establishes a model of economic growth unrelated to the use of resources and where the circular economy is foreseen in several of the policies contemplated in the Pact, among which stands out “the mobilization of the industry in favor of a clean economy and circulate”.

From a legal point of view, the circular economy is an instrumental principle to achieve later and lofty goals. There is no uniformity in its definition, and it has a transversal character with a clear transformative vocation that extends to a multiplicity of interrelated (but different) economic activities, such as production, consumption, waste management and markets for secondary raw materials (Alenza García, 2020).

The circular economy has had a greater prestige in the sustainable products sector and, especially, in the waste sector, since it determines how the principle of hierarchy is put into practice in its management, and it has given rise to legislative modifications - the tending perspective to the “zero waste” that changes the whole concept of waste to consider it as a resource (Nogueira López, 2020). It is important to emphasize that waste can be used for energy production, and, besides, the energy from residual biomass is considered renewable energy.

Indeed, the results obtained by the intermediate reports of the Action Plan are positive [COM (2017) 33 final] (European Commission, 2017), “Report on the implementation of the action plan for the circular economy” and [COM (2018) 29 final] (European Commission, 2018), “Framework monitoring for the circular economy”]. Nevertheless, by following the Green Deal and with the premise of greater ambition, a new Action Plan for the circular economy aiming at a cleaner and more competitive Europe was approved on 11 March 2020 [COM (2020) 98 final] (European Commission, 2020a), which is headed with the following sentence: “We only have one Earth, but in 2050 the world consumption will be equivalent to three planets”.

To achieve greater circularity of the production processes in the industrial sector, it proposes, among other actions, to support the circular and sustainable biologically based sector through the application of the Action Plan for the bioeconomy [COM (2018) 763 final] and the incorporation of ecological technologies related to an environmental verification system, which will be registered as an E.U. certification mark. The circular economy has such importance that one of the Plan’s proposals is, precisely, to adapt the E.U. legislation on waste to the circular economy and not the other way around, with the consequences that this entails. Also, aiming to the proper functioning of the internal market for secondary raw materials, the Commission will assess the possibility of developing the end-of-waste criteria in force at the E.U. level for certain waste streams. On the other hand, it promotes the role of circularity in future revisions of the national energy and climate plans and incorporates the circular economy’s objective in the E.U. Taxonomy Regulation.

These measures may affect the development of bioenergy. However, it is a canvas on which one must begin to manoeuvre to achieve concrete results; otherwise, the circular economy would remain a very ambitious principle with little practical impact. However, the E.U. cannot act alone, but a global transition towards a circular economy is essential. Therefore, the Commission will propose a global alliance, and, at the same time, it will ensure that free trade agreements reflect its objectives.

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# Biofuel and Bio-economy Nexus

**Sunzida Sultana, Saleha Khan, Ranga Rao Ambati, and Ravishankar Gokare Aswathanarayana**

## 1 Introduction

Worldwide renewable biofuels production is one of the largest viable alternatives to non-renewable fossil fuel and a sustainable core element for economic and environmental self-sufficiency. The prodigious growth in the emanation and usage of biofuels are catching increasing contemplation as a grade of renewable fuels with significance to improve national energy security, mitigate global warming, secure rural development and revitalize agricultural economic gains from export. At present, biofuels are the greatest tangible yield of the current and future bio-economy.

In many countries, bio-economy is a primitive economic sector, and an increasing bioenergy production by advanced industrial biotechnology transforms to the newest one. The term "bio-economy" or "bio-based economy" means economic activities that switch biological resources from the terrestrial and aquatic ecosystems to get food, feed, fiber, fuels, chemicals, materials and other domestic consumables in a sustainable way through ensconcing their secure and safe availability for future. According to the U.S. federal government, bio-economy refers to the global sustainability transition utilizing renewable land- and ocean-based biomass resources in bioenergy, intermediate, and final products for social, environmental, economic and

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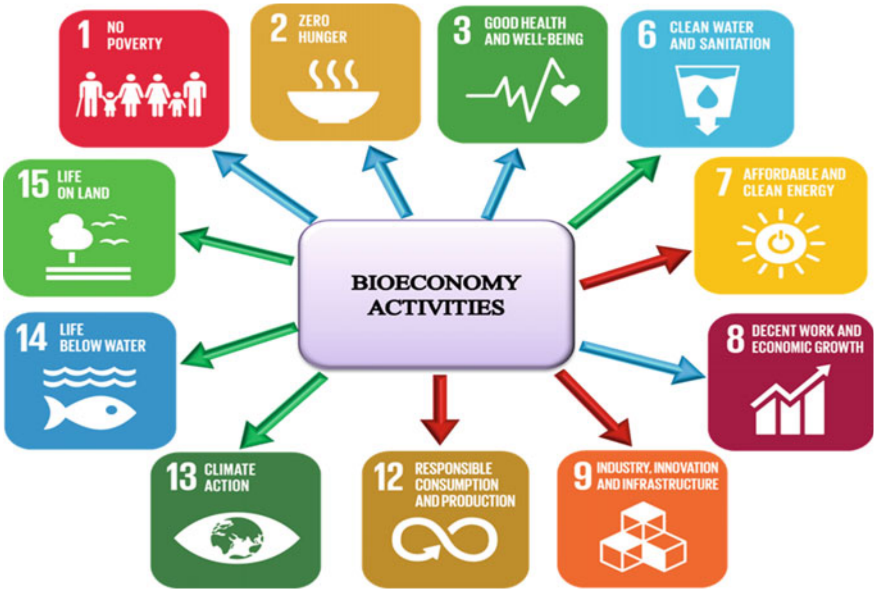


**Fig. 1** Sustainable development goals (SDG) influenced by bio-economy activities (photo is taken from sustainable development goal Fund). blue arrow: socioeconomic targets; green arrow: ecological targets; red arrow: clean industry and economic targets

national security benefits" (BRDB, 2016). The Organization for Economic Cooperation and Development (OECD) mentioned that a thriving bio-economy would drive potential shifts in the global economy over the next 30 years. Precise infliction of bio-economy activities plays a remarkable role in acquiring the Sustainable Development Goals (SDGs) (Fig. 1) in companies with biofuels related policies and regulations.

The fastening between biofuel and bio-economy is crucial in most developing and developed countries' gross domestic product (GDP) and employment. Nevertheless, modern biofuel production has a positive and negative nexus with the development of the world's bio-economy. The positive nexus between biofuel and bio-economy subsume proper utilization of biological resources, extenuation of greenhouse gases (GHGs), food security, employment opportunities, poverty alleviation and public health improvement. The positive aspects are an authentic commitment to achieving global sustainability. Over against, water scarcity, land-use change, soil degradation, deforestation, biodiversity loss and environmental pollution are covered as the negative consequences of biofuel and bio-economy nexus. Recently, negative aspects of biofuel expansion are needed to obliterate for being critical constraints in the Mondial bio-economic development.

The sustainability in biofuel and bio-economy nexus is today's demand to expel the negative effects and to ascent the positive outcome for the sake of benign environmental, social and economic development. Nowadays, country-wide government agencies and private sectors adopt different policies, different regulations and different incentives in biofuels generation with regard to governing the bio-economy. Further extensive research and development in biofuel and bio-economy nexus could fetch far-reaching amenities in regional, national and supranational levels per improvements in people's health and the whole ecosystem. The aim of this chapter is to focus on the relationship between the productivity of biofuel production and bio-economic development.

## 2 Definition of Biofuel and Bio-economy

***Biofuel***: In biofuel, the word "bio" refers to plant- and animal-based raw materials (agricultural and fishery products, forestry, animal waste, municipal wastes and microalgae) that are changed into fuel. According to OECD (2002), biofuel is a solid, liquid or gaseous fuel made by permutation of biomass resources such as bioethanol from sugarcane, charcoal, corn, wood chips and biogas from anaerobic putrefaction of waste materials. Usually, biofuels are defined as renewable primary and/or secondary fuels evolved directly or indirectly from organic biomass, which can be taken for the formation of bioenergy by more efficient and advanced conversion technologies. Primary biofuels use wood chips, fuelwood and pellets in an unrefined form for cooking, electricity generation and heating. Secondary biofuels are derived from the processing of biomass, including liquid biofuels such as bioethanol and biodiesel, which are applied in industrial processes and vehicles. Thermochemical processes and biochemical processes are two distinct processes of biofuel production.

***Bio-economy***: Mainly, bio-economy is termed as an association of economic activities connecting the invention, utilization, development and production of biological products and processes sustainably without lessening their availability for future generations. In the same way, bio-economy is also defined as the combination of all economic and industrial sectors and their affiliated services that use natural renewable biological resources (crops, trees, agricultural residues, algae and aquatic plants and wastes) in its generation processes to obtain different groups of outputs (liquid fuels, thermal energy, food and fodder, bio-products, chemicals, as well as cosmetics and medicines) for attaining global sustainability and eliminating environmental challenges. More comprehensively, bio-economy means establishing mergers with other industrial sectors (construction, manufacturing, engineering, urban planning, information and communication technology) to rehash human activity more bio-based, more competitive, more circular, more environmentally friendly, more inclusive, more nature-inspired and ultimately more sustainable (Rauschen & Esch, 2017). In most developed and developing countries, the concept of bio-economy put forward many future benefits linking with the development in human health, agriculture, environment and industrial sector.

***Nexus***: The word nexus is executed from the Latin word "nectere," which means "to bind or tie". Generally, nexus is defined as a bond or connection of mutual dependence or causality, especially between variables or series.

# 3 Nexus Between Biofuel and Bio-economy

The perpetuation of carbon–neutral biofuels mainly depends on three sustainability pillars: social, environmental and economic. For feasible nexus between renewable biofuel and global bio-economy, the three pillars of biofuel sustainability need to be gratified. Renewable biofuel production and related services have expressed some positive and negative nexus with bio-economic development. The positive aspects of biofuel assimilate efficient use of biological resources, greenhouse gas mitigation, food security, job opportunities, poverty alleviation and improvement on human health that potentially augment human social and economic progression. Contrariwise, the negative aspects of biofuel conjoin biodiversity loss, direct and indirect land-use change, forest alteration, water scarcity and pollution, which are specially marked as frantic jeopardy for the equipoise of environmental ecology.

## *3.1 Positive Nexus Between Biofuel and Bio-economy*

### 3.1.1 Biofuel Secure Efficient Use of Biological Resources

The dynamic evolution of biofuels is based on the use of biological materials (plant and animal sources) that is presented as a pathway for bio-economic globalization. In the bio-economy context, biological materials of primary and secondary biofuels derive from edible (food) and non-edible (non-food) organic matter. Primarily for cooking, heating or electricity production, primary biofuels such as wood chips, fuelwood, pellets and other organic components are used in an unrefined form. Elsewhere, secondary biofuels are divided into three generations: first-, second- and third-generation biofuels comprised of processing of biomass resources that can be used in various industrial processes and vehicles. Major naturalistic biological resources for the production of biofuels hold a wide range of traditional crops (sugarcane, oilseeds and corn), crop residues (rice hulls, wheat straw, corn stover, and cotton waste), energy-dedicated crops (trees and grasses), byproducts from agroindustry and paper industries, animal wastes (dung) and the organic wastage of urban areas (municipal wastes), microalgae and seaweeds. Considering bio-economy, the above biological resources are organized up to three biofuel generations feedstock for extending their efficient uses in a workable avenue without changing their presence for the future

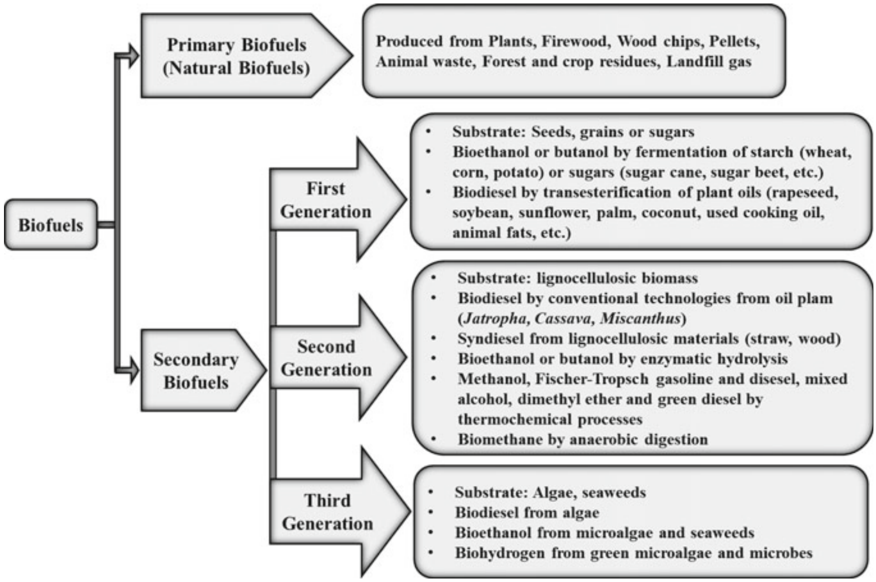


**Fig. 2** Classification of biofuels Singh et al., 2011 (Adopted from)

generation. Those three biofuel generations generally depend on different parameters, such as the type of feedstock and type of processing technology or their level of development (Fig. 2).

Most widely produced first-generation biofuels contain sugar and starch-based bioethanol, oil crop-based biodiesel and vegetable oil. Among first-generation biofuel feedstocks, sugarcane is a vast prominent commercial and biological crop for the propagation of bioethanol, bioenergy and sugar in the world (Long et al., 2015) because of good juice purity, high sugar content, healthy ecological adaptability and disease resistance. Recent Food and Agriculture Organization of the United Nations (FAO) statistics (FAO, 2017) showed sugarcane production rates in the top ten producer countries in 2016, where Brazil is alone peaking 768, 678, 382 tons (40.8% of world production) (Fig. 3). From the same source, world production of soybean, sugar beet and maize at a global level in the tantamount year was near 335 million tons from 121 million ha, 277 million tons from proximate to 45 million ha and 1.060 million tons from toward 188 million ha, respectively (FAO, 2017). Other crops such as sweet sorghum, wheat, barley, oat, cassava, rapeseed, sunflower, cottonseed are also largely manufactured for bioethanol and biodiesel production.

Lignocellulosic feedstocks like woody and herbaceous crops, woody and agricultural residues, industrial and municipal solid wastes are the hopefully advanced crops for second-generation biofuels production in subtropical and tropical countries. From the decades, even short rotation coppice and dedicated energy crops such as perennial grasses are enormously utilized as lignocellulosic biomass for bioethanol and biodiesel production. Many residues of lignocellulosic feedstocks have volatile

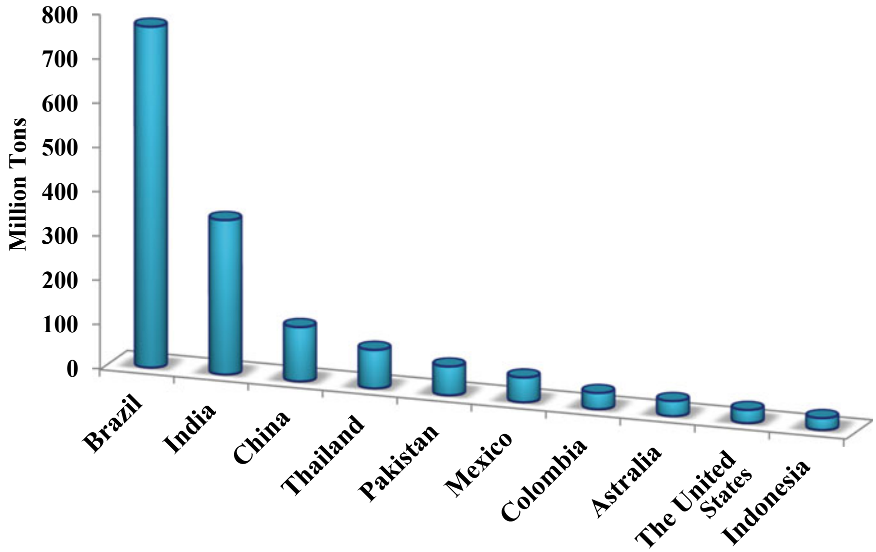


**Fig. 3** Top ten sugarcane producing countries in the world (2016) (FAO, 2017)

lucrative applications as fertilizer, soil conditioner and fodder, or are raw materials for different products such as recycled paper, medium-density fiberboard and particleboard. On the other hand, third-generation biofuels from microalgae, seaweeds and aquatic plants are currently considered as extremely winsome ulterior biological resources to biofuels production (OECD & IEA, 2017) in the future bio-economy.

### 3.1.2 Biofuel Inhibit Greenhouse Gas (GHG) Emission for Sustainable Bio-economy

The potential increase of greenhouse gas emissions has become one of the largest dangers in the universe. The growing energy demand and rising population trigger the precedence of fossil fuel-based power generation creating contravention combined with a rapid emission of greenhouse gases (Asumadu-Sarkodie & Owusu, 2016a). The leading greenhouse gas is carbon dioxide ($CO_2$), pre-eminently arising from human activity. The aggrandizement rate of $CO_2$ has tumid across the past 36 years (1979–2014) (Asumadu-Sarkodie & Owusu, 2016b, 2016c), "approximately 1.4 ppm per year before 1995 and after that 2.0 ppm per year" (Earth System Research Laboratory, 2015). In developing countries, energy-based $CO_2$ emissions will raise the global temperature above pre-industrial levels from 1.7 to 2.4 °C by 2040 and participate in increased floods, droughts and heatwaves with remarkable change to economic growth and population health (Intergovernmental Panel on Global warming, 2018). The replacement of fossil fuel with renewable biofuel is an excellent approach to mitigating greenhouse gas emissions (Fig. 4). Sometimes, it is contemplated that

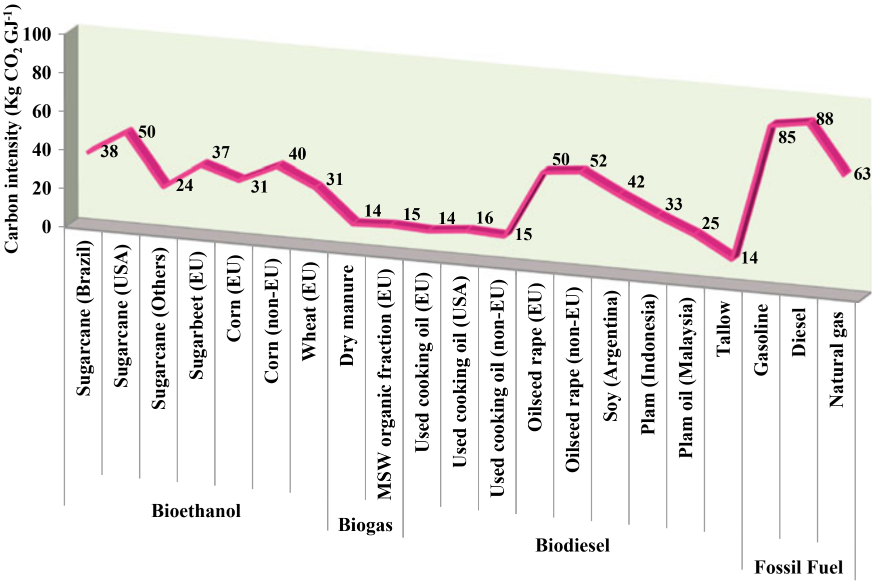


**Fig. 4** Carbon intensity of biofuels compared to traditional fossil fuels (data taken from UK-DfT, 2014a)

carbon emissions are the foremost reason for growing the demand for renewable biofuel.suggest that income is the

In recent years, renewable biofuel has been grown and used worldwide to boost the bio-economy and the quality of the environment by decreasing GHG emissions. Biofuels are often known as carbon–neutral fuels because they do not produce any net emissions of $CO_2$. The decline in total GHG emissions for 1990–2012 in European Environmental Agency (EEA) countries was about 22% (EEA, 2016) through biofuel development. Moore et al. (2017), Hanaki and Portugal-Pereira (2018), Subramanian et al. (2020), Skorek-Osikowska et al. (2020) and Sheriff et al. (2020) have got that biofuel production significantly diminish the $CO_2$ emission up to 20–90% than fossil fuels. Even 60% and 90% emissions are detruncated by ethanol production from sugar beet and sugarcane. Hitherwards, biodiesel production from maize, rapeseed and palm oil cuts emissions by 35%, 60% and 80%, respectively. For instance, da Silva et al. (2018) for sub-Saharan Africa and European countries, Ji and Zhang (2019) for China and OECD for Africa, reveal that there is a positive nexus between renewable energy demand and carbon emission. For the governments of maximum countries, intensive biofuel development is the primary target to preserve environmental quality and sustainable bio-economy since increasing greenhouse gas emission is an utmost global crux in the twenty-first century. Assume that developing and developed countries with more production and usage of biofuel can be capable of promoting better environmental quality.

### 3.1.3 Food Security Through Biofuel Generation

Food insecurity is a principal barrier in countries economic development. Recently, food security from increased biofuel production has gained the greatest attention in the global bio-economy. Food security includes four pillars: availability, access, utilization and stability according to the FAOs food security definition. By accessing nutritious and sufficient food all year round, people are considered as food secure. Increasing availability and access to food have been found in multiple areas with exceeding biofuel production (Leonardo et al., 2015). Furthermore, biofuels raise energy security that positively affects the utilization and stability aspects of food security via increasing credible storage and cooking of food.

Large-scale cultivation of biofuel crops cause land-grabbing and water stress; these, in turn, compete with agricultural products and negatively affects food security. First-generation biofuel production from agricultural food plants such as rice, maize, sugarcane, sugar beet, cassava, palm oil creates higher food prices and food shortages. In the past in Indonesia, when rice prices enhanced, mothers and children in poor households ate less as little money remained for more nutritious food, and they suffered from severe malnutrition. Chen et al. (2011) discovered that even with second-generation non-food biofuels, earning the biofuel mandate (without subsidies) in the USA on 2007–2022 would require to depend on maize for half of the occurrence leading to maximum maize prices.

In the last decades, intensive research on alternative fuel-producing species and small-scale cultivation for minimizing competition within the food sector reported that harvesting of non-food crops like *Jatropha curcas* on eroded land was advantageous for biofuel production. Also, the production of non-edible oilseed-based diesel in marginal land increase soil quality that has no competition directly with food crops. Application of organic fertilizer and pesticides in lands during biofuel feedstock production extends the productivity of soil and other agricultural food crops. More growth in agricultural food production contributes to food security and economic diversification through increasing food availability and utilization. The procreation of biodiesel along with energy efficiency and food productivity improvements became profitable for India to obviate the negative aspects of energy price hikes. At present, the large price of agricultural products is a constant threat to the viability of the biofuel expansion in several countries. Investments in research, infrastructure, technological innovations, government support and/or domestic support are necessary for biofuel development for declining high prices and food insecurity.

### 3.1.4 Biofuel Form Job Opportunities for Bio-economic Development

Unemployment and inoccupation in today's world are perceived as major obstacles to continual sustainable global bio-economy. Job securities are a principal determinant in the development of biofuel and bio-economy nexus. According to the International Renewable Energy Agency (IRENA), 855,000 direct and indirect new job opportunities from renewable bioenergy in the USA were recorded in 2018 (Energy Futures Initiative, 2019).

A secured job is a relevant part of global biofuel generation. Mainly, liquid biofuel (ethanol and biodiesel) industries and their subsectors provide great possibility in nationwide job creation. A recent study in the USA predicted that direct job opportunities from advanced biofuel production could create 190,000 full-time equivalents (FTE) jobs by the year 2022 (Renewable Energy & Jobs Annual Review, 2019). Further, in 2022, based on a farm gate feedstock price of US$ 60 per dry ton, approximately 134,000 new FTE jobs could originate from cellulosic ethanol production. Different job sectors in cellulosic ethanol production system encircles feedstock transportation corroborating nearly 43,000 new jobs, cellulosic feedstock production corroborating 32,000 jobs, local biomass storage operations corroborating 17,000 jobs, final bio-refinery facilities corroborating 13,000 jobs, ethanol distribution corroborating 15,000 jobs as well as construction sector corroborating 13,000 jobs, respectively (Fig. 5). Among several countries, in Brazil, 832,000 jobs, in European Union 208,000 jobs, in India 35,000 jobs, in France 24,400 jobs and in Germany 15,500 jobs are generated through renewable liquid biofuels industries that largely contribute to the global job sector (Fig. 6).

Recently, biodiesel production also provided substantial job convenience for securing bio-economic sustainability. According to National Biodiesel Board (NBB), domestic biodiesel production confirms over 60,000 jobs nationwide (NBB, 2019). However, IRENA reports that expansion of the U.S. biodiesel sector represented 72,300 jobs in 2018 (Energy Futures Initiative, 2019). Higher-income level from biofuel-related employments supports the countries to enhance the demand of more biofuel production and bio-economic activities since income growth expands the wealth of those countries. Eren et al. (2019), Ji and Zhang (2019) and Gozgor et al.

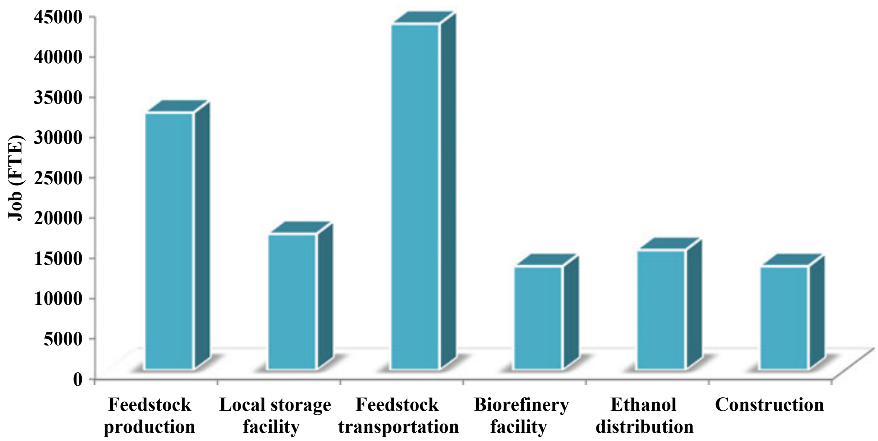


**Fig. 5** Direct job creation by the cellulosic ethanol production system at a farm gate feedstock price of US$ 60 per dry ton (Kim & Dale, 2015)

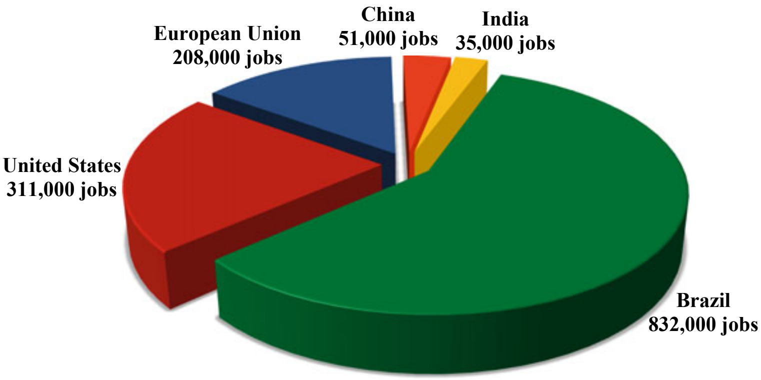


**Fig. 6** Direct and indirect jobs from renewable biofuels in different countries (data taken from Renewable Energy & Jobs Annual Review, 2019)

(2020) suggest that income is the cornerstone indicator of the bioenergy demand. Within several studies, Kahia et al. (2017) for oil-importing countries, Silva et al. (2018) for sub-Saharan Africa et al. (2019) for India et al. (2020) for OECD countries observe that income generates environmentally economical options for developing and developed countries bio-economy.

### 3.1.5 Effect of Biofuel on Poverty Alleviation

Poverty is a Mondial challenging phenomenon in twenty-first century (Gweshengwe et al., 2020). In rural regions of various countries, household poverty is affiliated with food scarcity, inoccupation, repugnant social and economic outcomes and poor health. Increasing growth in biofuel production is a critical piece to eradicate poverty in countries where poverty is condensed. The nexus of bio-economy with biofuel development brings new scopes for poverty alleviation as biofuel generation from natural biological resources emerges economic and environmental development. Modern biofuel expansion is a means of alleviating poverty and developing rural areas by reducing high food prices, increasing rural employment and income-generating activities among consumers, farmers and landless workers. Sufficient investments in biofuels production accelerate poverty reduction and economic welfare. For instance, in Indonesia, biodiesel production influences national production, labor demand, economic growth, unemployment, nutrition and poverty (Faurani Santi et al., 2018).

At present, biofuels feedstock production owing to small-scale farming has a strong positive effect on larger welfare improvements and poverty reduction. In Malawi and Mozambique, poverty is deeply pervaded, and the multidimensional poverty indicators find salient diversities between poverty profiles in both areas (Fig. 7). Based on the impacts of biofuel crop (e.g., Jatropha) cultivation in poverty alleviation, it is found that a smallholder-based project (Bio-Energy Resources Ltd

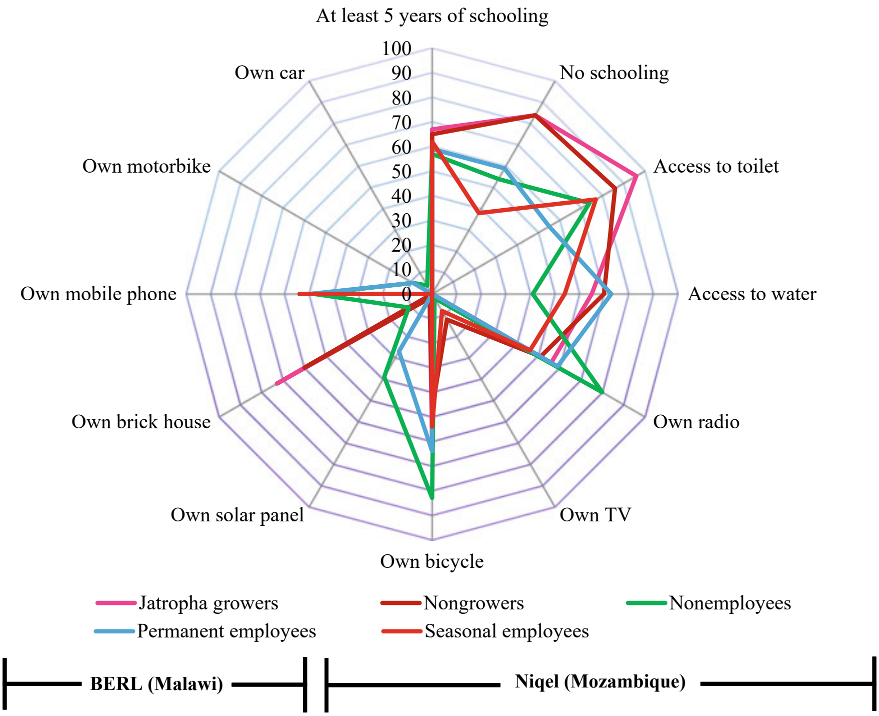


**Fig. 7** Multidimensional poverty indicators for farmers in Malawi and Mozambique (% of households) (data Taken from Maltitz et al., 2016)

(BERL)) in Malawi tended to have better ingress to schooling, permanent water and housing compared to a large-scale estate-based block plantation (Niqel Lda (Niqel)) in Mozambique (Fig. 7) (Maltitz et al., 2016). Hence, poverty alleviation from biofuel enhancement heightens bio-economy by means of imported fossil fuel reduction, rural development, more incomes, job opportunities, higher land rental values and lower food costs.

### 3.1.6 Biofuel Incite Improvement on Public Health

The burning of traditional biomass and fossil fuel for transportation, cooking and heating invent many impediments to good human health. From biomass and fossil fuel burning, gaseous and particulate air pollutants are exposed to the air that causes chronic obstructive lung disease, chronic bronchitis, emphysema and cancer through human inhalation. Redemption of miscellaneous air pollutants, including carbon monoxide (CO), hydrocarbons, nitrogen oxides (NOx), particulate matter (PM) and volatile organic compounds (VOCs), is normally lower from biofuels to fossil fuel. Renewable biofuels assuage health and environmental complications by decreasing different pollutants occurring from fossil fuel sources. Biofuel, in relation to bio-economy, introduces several facilities and improvements in people's health with enhancing environmental salus.

Among biofuels, biodiesel is the sole substitute fuel that perfectly accomplished the health effects testing requirements of the 1990 Clean Air Act Amendments because of low sulfur emissions compared to regular diesel. A claimed potential health benefit of biodiesel is less harmful to human health relative to petroleum diesel fuel. Besides, biogas support programs from various household surveys published that problems like asthma, lung problems, respiratory illness and eye infection were curtailed after constituting a biogas plant. Improved access to clean bioenergy could simplify the ebullience of water before swallowing, resulting in a decline in the threats of waterborne diseases. Prosperity in public health through biofuels generation retrenches medical expenditure of rural families, improve work and school attendance. The debate about biofuels impacts on human health is very common, and further significant research and evidence are needed to end this argument. In spite of that, renewable biofuels upliftment should be unperturbed to increase environmental balance as well as public health.

## *3.2 Negative Nexus Between Biofuel and Bio-economy*

### 3.2.1 Land-Use Change Due to Biofuel Extension

Land-use change (LUC) performs a vital role in the earth's GHG emission as it added 660 ± 290 Gt $CO_2$ to the atmospheric $CO_2$ from 1750 to 2011. An accretive demand for food, fiber and fuel becomes a primary factor for the majority of LUC (Harris et al., 2015). Alteration of rainforests, grasslands, savannas and peatlands to produce food crop-based biofuels expel a huge amount of carbon from plant and soil biomass, making a "biofuel carbon debt" that can take years to reimburse. Carbon sequestration, water filtration and biodiversity preservation are valuable environmental services that are luxated by changes in land use with increasing GHG emissions.

Biofuel production provokes both direct land-use change (DLUC) and indirect land-use change (ILUC). DLUC occurs when feedstocks for biofuel production directly transfer formerly fallow areas (such as forests and grasslands) into croplands. ILUC refers to the prolapse of feed and food crop production to fresh land areas previously not used in plowing for appeasing additional demand of biofuel feedstock.

Latterly, indirect land-use change has been a major issue in different continents. Research on the indirect land-use change attached with US corn ethanol discovered that ILUC emissions converted from 10 to 340 g $CO_2$ eq. $MJ^{-1}$. More recently, Pavlenko and Searle (2018) identified that ILUC outcome from lignocellulosic biomass such as perennial grasses, short rotation coppice (SRC), miscanthus and switchgrass strongly affects the assumptions of yield, land transformation and carbon

**Fig. 8** Female farmer's land was purchased by a foreign investor (photo is taken from Wikimedia Commons)

stocks deflect on the final results. Many international companies and foreign investors buy large tracks of land to emergence biofuel feedstocks that deadly reduce agricultural land (Fig. 8). Some studies about land footprint through biofuels found that bioenergy conduct undesired changes and conversions in land use. Nowadays, the land becomes a comparatively inaccessible resource because its availability enhances at a slower rate compared with the rest of the bio-economy. Minimization of "ILUC" effects could come by using "potential abandoned or marginal land" in renewable biofuel production.

### 3.2.2 Biofuel Dilate Biodiversity Loss

Biodiversity loss relevant to biofuel generation and bio-economic development affects exhaustive natural ecosystem through habitat loss and degradation, the introduction of invasive exotic species used as feedstocks, overexploitation and nonviable use of land superfluous nutrient load and other forms of pollution. Alteration of agricultural land, grassland and forest is the main driver for decrement species richness, abundance and wild biodiversity in tropical countries. Biofuel-driven agricultural expansion in the Amazon, Atlantic Forest and Cerrado biomes of Brazil for increased biofuel demand exacerbate the risk to endanger area's rich in endemic bird species diversity. On the contrary, the agrobiodiversity loss is dependent on large-scale crop monoculture, using a parochial pool of genetic components with reduced use of traditional variants. That low levels genetically diversify grasses exert as feedstocks (e.g., sugarcane), affix the impressionability of crops to new invasive species and diseases. Switchgrass, eucalyptus and some *Miscanthus* species show this type of invasiveness.

Of late, first-generation biofuels turn out harmful for biodiversity because of the high requirement of intensive cultivation and agrochemicals in feedstock production (Elshout et al., 2019). Compared with first-generation, second-generation biofuels from perennial crops have both positive and negative influences on biodiversity. Plant-based lignocellulosic feedstock, for example large-scale SRC willow, requires fewer manures and pesticides and less human interference during the growth period, which is helpful for some bird species, butterflies and flowering plants. Correspondingly, low-input high-diversity compositions of native perennials grassland for biofuel production may improve migratory avian species diversity. At the same time, excessive forest assessment and increased use of agricultural residue for second-generation biofuels production disturb the wildlife biodiversity and reduce the niche habitats. Third-generation biofuels from microalgae would also be a concern as large-scale microalgae cultivation provide a potential threat to littoral biodiversity through the onslaught of noxious microalgal species into shallow coastal ecosystems, exempli gratia, seagrass bed, mangroves, coral reefs, mudflats and salt marshes.

The eventuality of biodiversity loss is tenacious to measure due to the existing knowledge gaps on biodiversity outcomes from bioenergy in the scientific community. Marginal or degraded land use, significant land-use planning, better management of agricultural, environmental and rural development sectors, elimination of forest transformation, suitable ecological corridors and ecological buffer zones are proposed to abate the negative aspects and promote biodiversity for sustainable bio-economy.

### 3.2.3 Eventuality of Biofuel Induced Forest Alteration in Bio-economy

Forest is one of the biggest carbon sinks on the earth. According to FAO (2012), the forest is defined as land spanning more than 0.5 hectares with trees bigger than 5 m and a canopy cover of more than 5–10%, or with a combined cover of trees, bushes and shrubs able to reach these thresholds in situ. In the global bio-economy, forests are the main purveyor of biofuel production. In higher-income countries and in areas with high forest density, biofuels from forest wood have gained attention during the last decades as they continuously displace fossil fuels from the twentieth century. From forestry, around 88% of the biomass is utilized for bioenergy in the world, following the World Bioenergy Association (Kummamuru, 2017). Forest mainly provides wood and forest residues such as small trees, tops, leaves, needles and branches for biofuel creation.

Nowadays, the growing demands of renewable biofuels have contributed to forest alteration that is very high and problematic in tropical and subtropical countries (Fig. 9). Forest alteration means the conversion of tropical forest or natural vegetation to cultivate biofuel feedstocks, creating environmental complications and "carbon

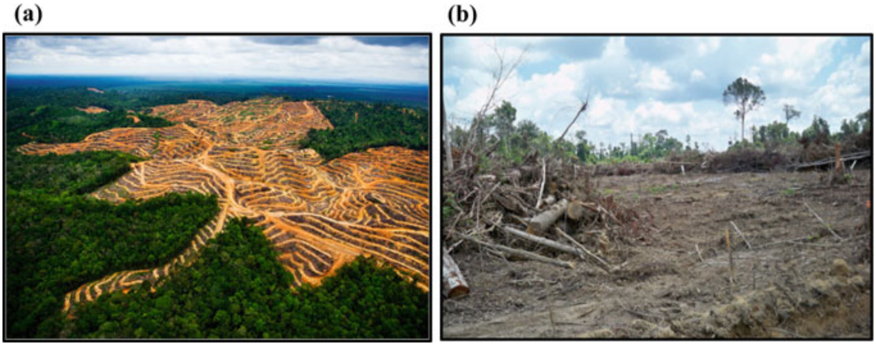


**Fig. 9** Forest alteration by biofuel production (photo (a) is taken from Conservation Ecology, October 20, 2011, and photo (b) is taken from EUobserver, June 15, 2018)

debt" that could take decennary or even a century to offset. Transformation of forest linked to biofuel generation have dramatic effects on nature, as it breaks down soil organic matter, release soil carbon (captured by forest residue) and reduce forests $CO_2$ absorption. Cutting and burning of forest wood for biofuel yields build unexpected large quantities of $CO_2$ eduction. Biodiesel production from palm oil is associated with forest conversion, which originates 3–40 times greater GHG emissions than diesel in Malaysia and Indonesia. Moreover, in Europe, Indonesia, Brazil and Tanzania, forest destruction via *biofuels* production causes climate change, land conflict, loss of wild biodiversity and ecosystem services, labor issues and indigenous rights issues (Hance, 2015). Increasing climate change and high greenhouse gas emissions due to biofuel-related deforestation affect public health disproportionately. Considering all these effects of biofuel-induced forest alteration, bio-economic development becomes questionable in the case of biofuel procreation. Priority on mass afforestation, crop plantation in marginal land and strict management practices of forest are especially insistent for the sound biofuel and bio-economy nexus.

### 3.2.4 Biofuel Expansion Accrete Water Scarcity

Water is an essential limiting factor for the production of biofuel feedstocks and bio-economy. The total global water consumption with increased agro-based biofuels production could rise notably by 2050 (Hammond & Li, 2016). Many crops of first-generation biofuels such as sugarcane, maize and oil palm assert a large amount of water at mercantile yield levels than drought-resistant crops (e.g., Jatropha). High-rainfall tropical areas are suitable for 76% sugarcane production in Brazil and 70% maize production in the USA. In arid and semi-arid regions where water is inaccessible and highly volatile throughout the year, the growth of perennial plants like jatropha and Pongamia on marginal lands has some irrigation water requirements in the summer season. For washing plants, seeds and evaporative cooling, a huge amount of water is also used during biofuel production. The production of bioethanol and

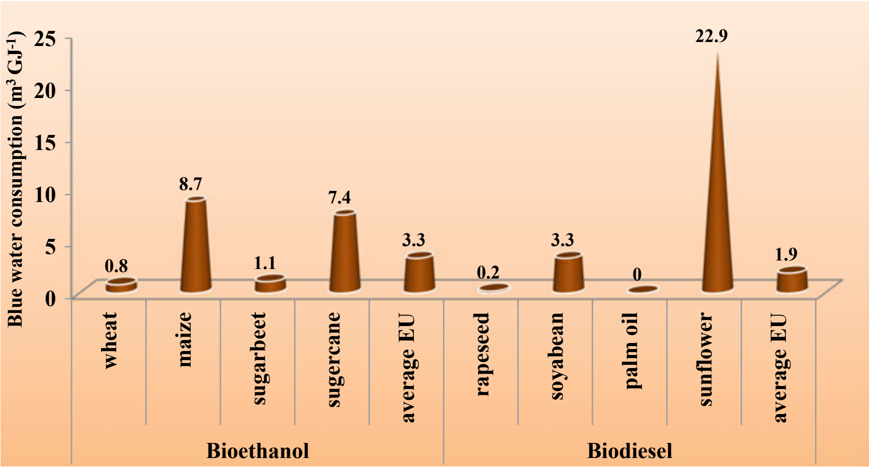


**Fig. 10** Bluewater consumption for biofuels consumed in Europe. Based on data from Berger et al. (2015). Data labels represent the average values

biodiesel in Europe consumes 3.3 $m^3$ $GJ^{-1}$, and 1.9 $m^3GJ^{-1}$ blue (surface) water, which is respectively 40- and 60-times higher compare with fossil fuels (Fig. 10). Consequently, high water consumption in biofuel production transpires water-level imbalance, the higher marginal cost of water, water scarcity and bio-economic transience in many countries. The available natural water resource is already near its hydrological limit for numerous irrigated sugar-producing regions in eastern and southern Africa and north-eastern Brazil.

In sparse water areas, antagonism for irrigation water for certain feedstocks can decrease food production. More biofuels crop production will most likely affect the water quality and quantity. For instance, excess nitrogen and phosphorous runoff, the introduction of pesticides and chemicals into waters is occurred by conversion of pasture or woodland into maze fields as maize require the highest amount of fertilizer and pesticides per hectare. Untreated contaminated wastewater discharged from the palm oil industry, agrochemicals and fertilizers use during cultivation has been the main source of water pollution (eutrophication) in Malaysia and Indonesia that emerge the violation of the indigenous people rights. Environment-friendly farming practices and appropriate new technologies are necessary to mitigate the water scarcity problems derive from biofuel development for enduring bio-economy.

### 3.2.5 Influence of Environmental Pollution on Bio-economy

The biofuel's sector is not constantly remunerative for the environment, although biofuels emerge as a strategically largest contributor to greenhouse gas emission in the global bio-economy. Some negative environmental consequences, as well as social and economic consequences, are manifested in third-world countries. Soil pollution, water pollution and air pollution are the main aggravating environmental pollution in the twenty-first century. This environmental pollution is interlinked with the biofuels sector due to the production, utilization and combustion of biofuels.

Biofuel production highly requires freshwater and land, leading to freshwater depletion, water pollution, loss of wildlife habitat, reduced ecosystem services and even increased indirect antibiotic resistance. Vast amounts of fertilizers, agrochemicals and protecting agents are used in soil for cultivating lands and intensive agro-based biofuel feedstock farming activities that originate many pollutants and a high degree of pollution. The major liable pollutants for the contamination of the environment are particulate matter (PM), hydrocarbons, carbon monoxide (CO), nitrogen oxides (NOx) and volatile organic compounds (VOCs). Emersion of acidic gases and pollutants from the use of fertilizers, agrochemicals and pesticides create eutrophication and acidification in the soil and water. Several studies indicate that impacts of acidification and eutrophication are higher from biofuels instead of fossil fuels (Arpornpong et al., 2015; Belboom et al., 2015) (Table 1). Compared to fossil fuels, first-generation bioethanol has till 3 times greater acidification and 3 to 20 times greater eutrophication, as well as first-generation biodiesel, also has 30–70% higher acidification and 3 to 14 times higher eutrophication. Similarly, second-generation bioethanol from switchgrass and straw exhibits both acidification and eutrophication. Moreover, third-generation algal biodiesel also shows more acidification and eutrophication than fossil fuel. Exposure of water and soil pollutants to human health occurs from inhalation, consumption or dermal contact resulting in poisoning and skin irritation by carcinogens and infectious agents.

In addition, ambient air pollution accrues from biofuel during the harvesting and burning of solid fuels and biomass. In Brazil, straw is burned in the fields to produce sugarcane ethanol, which is the predominant source of PM (Scovronick et al., 2016), conducting a toxicological risk during the burning season (usually about 6–8 months per year) as these particle concentrations rise by 100% or more in adjacent cities by burning. The higher proportion of smaller particles or ultrafine particles (less than 100 nm diameter) is generally suspended in the air for a longer time and freely inhaled and penetrated more deeply into population health. Particulate matter (PM) with other pollutants of human health concern includes ground-level ozone, oxides of nitrogen (NOx), CO, $SO_2$,and various air toxins such as acetaldehyde and benzene enhance morbidity and mortality from cardiovascular and lung diseases and certain cancers. Labors, women, schoolchildren and adolescents who are working and living near the straw-burning areas are spontaneously affected by respiratory diseases, such as pneumonia and asthma. This strong evidence is found in studies on health conditions in the case of sugarcane ethanol in Brazil (Le Blond et al., 2017; Scovronick et al., 2016). Along with sugarcane straw burning and liquid biofuels, all stages in the biofuel life cycle ensure air pollution and human health difficulties (Fig. 11). However, significant judicious application of organic nutrients and/or agrochemicals, careful soil and water management and good agricultural practices will require for restraining environmental pollution.

**Table 1** Acidification and eutrophication of different biofuels

| Biofuel generations | Feedstock characteristics | Biofuel types | Conversion technologies | Feedstocks | Acidification[a] | Eutrophication[a] | References |
|---|---|---|---|---|---|---|---|
| First-generation | Food-based crops/edible biomass | Bioethanol | Alcoholic fermentation | Corn | 1.4–3 | 4.4–20 | |
| | | | | Wheat | 3 | 5 | Belboom et al., (2015) |
| | | | | Sugar beet | 1.4–1.8 | 6–15 | |
| | | | | Sugar cane | 2 | 2.8 | |
| | | Biodiesel | Transesterification | Rape seed | 1.3–1.7 | 3.1–5 | |
| | | | | Soya bean | 1.3–1.7 | 4–5 | |
| | | | | Palm oil | 1.3 | 14 | Arpornpong et al., (2015) |

(continued)

**Table 1** (continued)

| Biofuel generations | Feedstock characteristics | Biofuel types | Conversion technologies | Feedstocks | Acidification[a] | Eutrophication[a] | References |
|---|---|---|---|---|---|---|---|
| Second generation | Non-food crops/non-edible biomass | Bioethanol | (1) Pretreatment, hydrolysis, and alcoholic fermentation (2) Gasification followed by chemical or microbial synthesis | Short rotation coppice | 0.45 | 1.2 | |
| | | | | Switchgrass | 1.1 | 3.2 | |
| | | | | Straw | 1.6–3 | 2–3.6 | |
| | | Biodiesel | Transesterification | Used cooking oil | 0.2 | 0.63 | |
| | | | | Jatropha | 1 | 1 | |
| Third generation | Microscopic biomass/algal biomass | Biodiesel | Transesterification | Algae | 2.6–3 | 2.1–3.2 | |

[a] the values represent the ratio of impacts from biofuels over fossil fuels and are dimensionless

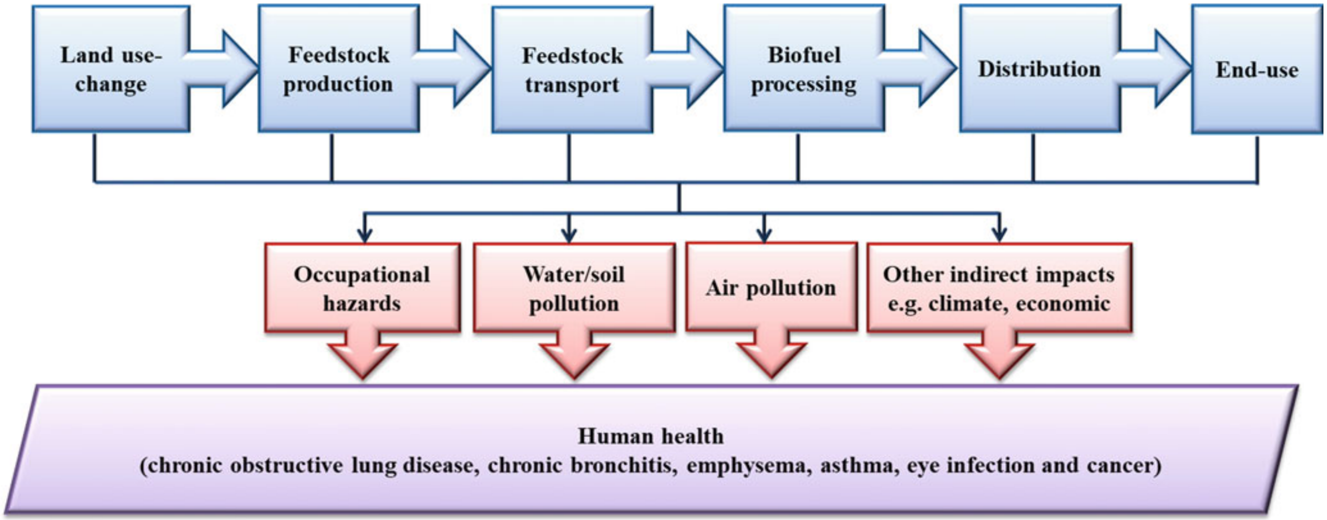


**Fig. 11** Schematic depicting the life cycle and major pathways to health associated with liquid biofuel production and use (Adopted from Scovronick & Wilkinson, 2014)

## 4 Government and Private Sectors Participation in Biofuel and Bio-economy Nexus

The joint role of government and private sectors purvey a wide variety of profits in worldwide biofuels development, including lower GHG emissions than fossil fuel counterparts, employment generation, increased household energy security, economic development and the creation of environmental and health viability. In general, the effectiveness of biofuel and bio-economy nexus hinge on the government and private sectors participation to amplify eco-friendly biofuels deployment.

Governments of many countries have established participatory governance, policies and different financial initiatives toward acquiring bio-economic sustainability by reducing manifold constraints. Global biofuel yields increased sixfold from 2000 to 2010, and a rising number of countries are taking biofuel promotion policies. Policies are crucial for indicating the direction of biofuels development at the global and national levels. In 2012, Bioenergy and Food Security Criteria and Indicators (BEFSCI) destined the following key incentives:

***Transfers/Subsidies***: Subsidies are served as a safety net and direct or indirect pecuniary fulcrum for the farmers or other actors engaged in the production and distribution of biofuels in most countries, for instance minimum support price program for jatropha cultivators in India.

***Tax credits/Fiscal Incentives***: Tax incentives or penalties are the major policy component for enkindling the demand for biofuels and can drastically influence the competition between biofuels and other energy sources. For example, under Brazil's Social Fuel Seals, biodiesel producers are given tax credits.

***Grants***: Grants is ordinarily applied to foster good practices in biofuel prolongation, encourage development and research and promote headway of technologies, for instance the US program of Sustainable Agriculture Research and Education (SARE) program.

***Soft Loans***: Soft Loans is the widely used instrument by varied governments to accelerate biofuels. For example, the soft loan program of the Thai government incentivizing rural farmers to start growing bioenergy crops (APEC).

To exacerbate biofuel development, many Asian countries like China, Malaysia and Thailand, often adopt the above supplementary policies. In addition, governments with supportive policies of biofuels boost the interest of the private sectors. Private–public partnerships (PPPs) are easily contributed in redacting innovative technologies and incentives for concerting sustainable development of biofuel and the bio-economy. In recent decades, most non-government private sectors of biofuel production and consumption support biofuel industries, create employment, provide financial services, increase mass awareness and stimulate economic growth, which is endorsed by the government.

Local government and private sector altogether establish jatropha plantations for biodiesel production in rural Philippines and Ghana, respectively. The cause of this greatest attention in jatropha plantation by the governments, donors and private sectors is its favorable environmental and socioeconomic satisfaction. Likewise, Santika et al. (2019) found that swift development of palm oil cultivation in Indonesia, mainly in Sumatra and Kalimantan (Indonesia Borneo). New research by proactive private consultants, government agencies and academic researchers has noted potential microalgae cultivation for quantifying the advantages of alternative biofuels in Australia. More recently, the private sectors of Bangladesh, along with the government, has taken few initiatives for biofuels production as it does not commercially produce yet. Therefore, further governments and private sectors participation are expected to retain a plausible future by the services of alternative renewable biofuel that shift bio-economic development toward more sustainability.

## 5 Conclusions

The global concept of bio-economy is still now in the development phase. The positive and negative consequences of renewable biofuel generation and utilization greatly affect the nexus between bio-economy and biofuel in different countries. Enlargement of positive aspects and palliation of negative aspects are demanded to measure the opportunities and risks of a sustainable bio-economy. Government and private sectors of several countries are very active and giving prime concern to fostering renewable biofuel production and guaranteeing long-lasting bio-economic development via appropriate management, umpteen policies, research and innovative initiatives. It is also necessary to create local, regional and international cooperation and coordination for securing viable biofuel and bio-economy nexus. After all, a low carbon bio-economy remarkably strengthens the present and future biofuel sector by consummating sustainable development.

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# Adopting a Circular Bio-economy: The Biorefinery Concept

**Anita V. Handore, Sharad R. Khandelwal, Mrunal S. Ghayal, and Dilip V. Handore**

## 1 Introduction

The recent world population is 7.9 billion people as of 28 December 2021 and is estimated to be ten billion by 2057 (Worldometer, 2021). Sustainable development addresses the environmental challenges caused due to climate change including global warming, food security, waste disposal and natural resource reduction, etc. Various global and regional measures are underway to mitigate these risks and try to create viable bio-based economy approaches which span across industries, regions, and even end consumers.

For the last two decades, sustainability seems to be important in the research and political issues However, distinct understandings and applications w.r.t. sustainable development, ecological, economic, and social goals have been facing numerous challenges. By and large, society is very well aware of the climate emergency, challenging the fate of mother earth and working on sustainable policies. The globalized world which is at risk due to climate change, global warming, natural resources depletion, and needs requires the adoption of a new productivity and consumption system certifying its sustainable economy.

Movements like the 2030 Agenda and the United Nations (UN) Sustainable Development Goals Paris Agreement within the framework of the United Nations Framework Convention on Climate Change, i.e., UNFCCC in effect as of 4 November

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2016. To regulate the temperature rise, or assurance of the European Union (EU) for achieving a climate neutrality coalition till 2050, represents an opportunity in the effective movement towards a sustainable economy. In this context, sustainable and correlational application of concepts like bio-economy (BE) and circular economy (CE) could be a intersect ailment which could strongly affect almost all the economic sectors by promoting the circular bio-economy.

### *1.1 Bio-Economy (BE)*

Bio-economy is defined as the production of renewable bioresources and conversion of waste streams to value-added products like bioenergy and bio-based products, etc., (European Commission, 2012).

#### 1.1.1 Advantages of the Bio-economy

- Bio-economy is the open and innovative approach involving the collaboration of diverse stakeholders, adopting dialogue and cooperation at a global level.
- It is linked to prudent management of all the natural resources.
- It helps to promote the research across disciplines and borders.
- It could directly replace the fossil carbon in diverse applications.
- It has the prospective to create employment in urban as well as rural settings.
- It could help minimize emissions of greenhouse gas by reducing fossil fuel dependence and help to restructure energy and food production.

As per European Union and Organization for Economic Co-operation and Development, there are different types of bio-economy, ecological economy symphonic with biosphere capacity, economy based on science driven by industrial biotechnology, and biomass-based bio-economy. Even if there are certain divergences, the biological belongings are part of various views concentrated on the bio-economy with biorefineries as the key proposals of sustainability (Conteratto et al., 2021).

## 2 Circular Economy (CE)

It is a framework related to productivity and consumption, involving sharing, leasing, reusing, repairing–refurbishing, and recycling the remaining materials and products, thereby extending their life cycle. Moreover, when any product reaches its expiry, the material could be retained within the economy wherever possible. This could support creating its value ahead.

This framework differs from other traditional economic models. It relies on a huge amount of low-priced, easily accessible materials as well as energy. The model

**Table 1** Aspects of circular economy and bio-economy w.r.t. sustainability dimension

| Concepts | Sustainability dimension | |
|---|---|---|
| | Social | Environmental |
| Bio-economy (BE) | Rural policy; research and development in health science, sustainable development | Bio-security, types of crops and species, risk factor, yield, green investments |
| Circular economy (CE) | Economy, development, utilization | Recycling, reuse, effectivity, industrial association, green supply chain |

has been designed to have a specified life span for encouraging the consumers. Besides, the consumers could be provided with more innovative durable products which could extend the quality of life as well as save money on a long-term basis. Thereby, it could provide benefits such as reducing adverse impact on the environment, improving security to supply raw materials, it will upturn competitiveness, motivating innovation, and could help to create jobs by boosting the economy.

### *2.1 Overlaps and Differences Between Circular Economy and Bio-economy Strong Overlaps*

It is found that both bio- and circular economy shares the same targets concerning a sustainably resourceful world along with a reduced carbon footprint. Although they are different, they have complementary approaches, as these economies eliminate the use of additional fossil carbon, contributing to climate change (Table 1).

Bio-economy (BE) is responsible for replacing fossil carbon with renewable carbon sources like agricultural biomass, forestry, and marine environment including by-products, wastes, etc. The circular economy (CE) strengthens the resource processes' efficiency and also utilizes recycled material for reducing the use of additional fossil carbon (Fig. 1).

## 3 Circular Bio-economy for Sustainable Development

The strategic combination of bio- and circular economy favours economic transformation of the model and changes the habit of existing consumption. Hence, their combined practice could inspire a sustainable use of natural resources. With the application of a systematic approach, the efficiency of natural resources could be improved. This could help to reduce the burden on the environment. If we continue to depend on the high consumption of natural resources, there will be a serious and uncontrolled ecological crisis resulting from these inadequate resources. However,

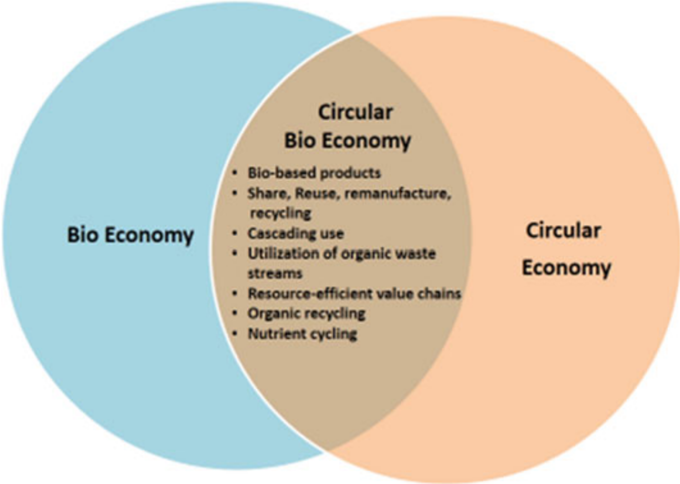


**Fig. 1** Circular economy and other industrial sectors. Adapted and redrawn from Carus (2017), Newton et al. (2017)

increasing demand for food, feed, bioenergetic, and biomaterials might lead to over-exploitation of such natural resources (Calicioglu and Bogdanski, 2021; Dodson et al., 2015; Zabaniotou, 2018).

Bio-economy-based circular approach will allow us to maintain values and utilization of material as well as to support the control of waste generation of non-recycled waste by prolonging the life of recycled products and material (Krishnan et al., 2020). However, in the circular economy (CE), the bioresources are placed for a long time to ensure the complete utilization in the production chain. This could promote the use of biomass by circularly replacing all the fossil fuel-based resources. Thereby, supplementary sustainable products could be achieved, and by-products and waste in the chain could be reduced. (Broring et al., 2020; Sheridan et al., 2016).

These economies should pay integrated attention to global environmental sustainability w.r.t. removal of biomaterials, which should be harmless for the protection of biodiversity (Guan et al., 2021; Alhola et al., 2019).

In this regard, the concept of circular bio-economy (CBE) attempted to promote both sustainable development and circularity. The economy denotes the cascading application of biomass from bioresources to a systemic approach. This offers efficient biomass utilization including wastes and side streams for the sustainable production of multiple high-value products.

This economy tends to adopt the circularity principles of both bio-economy (BE) and circular economy (CE). Therefore, the existence of a circular bio-economy (CBE) makes sense only if these concepts complement each other (Amato et al., 2018) (Fig. 2).

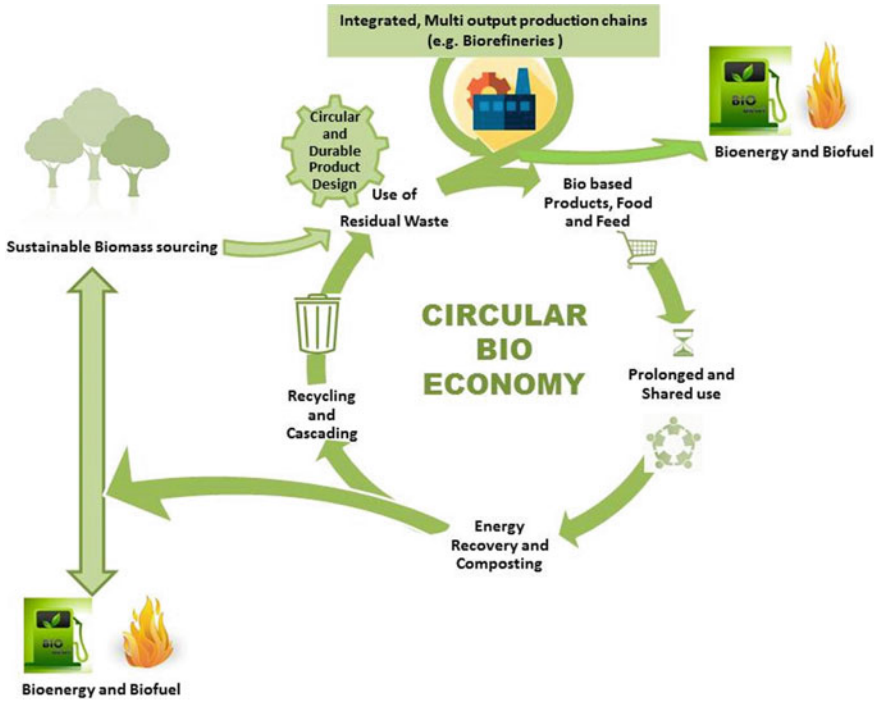


**Fig. 2** Circular bio-economy and its elements. Adapted and redrawn from, Stegmann et al. (2020). https://www.sciencedirect.com/science/article/pii/S2590289X1930026X?via%3Dihub

The CBE emphasizes sustainable, resource-efficient biomass valorization in integrated, multi-output manufacturing chains like biorefineries simultaneously, and utilization of wastes/residues by upgrading the value of biomass for circularization.

Which could focus on environmental or socio-economic aspects. This is preferably reflected as a significant pillar of sustainability. In this regard, the cascading stages should be appropriately targeted at maintaining the quality of resources by adopting the bio-based value pyramid and hierarchy of waste.

In this context, a circular bio-economy (CBE) could be encouraged by a biorefinery framework which reflects a holistic approach comprising the valorization of bio-feedstock for efficient bio-production of value-added products via an eco-sustainable production chain (Zuin, 2016). The utilization of biogenic organic wastes fulfils the need for feedstock along with the establishment of associated robust technologies for its sustainable transformation into valuable products. Besides, there is a need to design and implement many strong technological schemes for accomplishing efficient conversion yields.

The cohesive biorefinery platform mixes the raw materials and produces chemical platforms and bioenergy by organic material transformation.

The combinational processes and equipment lead to an appropriate platform to enhance the potential of a circular bio-economy (CBE) (Yue et al., 2014).

In this regard, an adaptation of the circular bio-economy w.r.t. biorefinery platform could support the assimilated production of various products like energy, platform chemicals, biopolymers, etc. Means of thermochemical and biochemical processes could be the communal passage for efficient transformation of bio-based resources (Moncada et al., 2016).

## 4 Biorefinery Models

Biorefinery is a sustainable bioprocess which could resourcefully utilize the biomass as a resource for the production of various economic products and different metabolites like carbohydrates, proteins, lipids, bioactive compounds and biomaterials, etc. (IEA Bioenergy, 2019).

It is among the facilitating strategies of the bio-based circular economy which closes the loop of fresh/raw resources, water, minerals, carbon, etc. These days, waste biorefineries have been receiving higher interest, as it represents a competent waste management approach (Leong et al., 2021; Mishra et al., 2019; Hoornweg et al., 2013; Dahiya et al., 2018).

Biorefinery should process all types of biomass like energy crops, organic residues, and various types of wastes, for the production of several products. Therefore, raw materials finding for processing into the high-valued product is one of the key aspects of this model. Because, processing of raw materials at a high scale and residual production at a low scale could support maximizing the eco-sustainability of biorefinery (Demirbas, 2009; Moncada et al., 2013).

These days, sustainability aiming for energy efficiency, food security, and material and environmental protection have become key drivers for the production of bio-based alternatives, resulting in increased advancement as well as the development of the biorefinery concept. This highlights the conversion of biomass into a plethora of products alternating from bulk products like bioenergy and/or substrate chemicals and fine chemicals, flavours, fragrances, etc.

The biorefinery concept has been employed for producing valuable products using different feedstocks like lignocellulosic/algal/microbial biomass, food wastes, microbial-treated wastes and manures, etc. Recently, enzyme-based technologies have been established and integrated with biorefinery for the generation of advanced biofuels, etc., (Ubando et al., 2020).

There is a sequential appearance as well as utilization of 1G (first generation) including cane, wheat, rice, edible vegetable oils, etc., 2G (second generation) including biomass resources, forestry residues, non-food crops, etc., and 3G (third generation) including bio-feedstocks, microalgae, etc., for getting high-cost efficiency, improved renewability, and environmental concerns. (Moncada et al., 2016). In the last few years, the use of agricultural/industrial wastes related to food, textile, etc., in the form of feedstocks has attracted excessive attention to develop the waste biorefineries (Venkata Mohan, 2014). The main appealing motives for this concept are the surplus availability of biogenic high residual nutrient value of wastes and significant environmental and economic prospects. Worldwide, municipal solid waste (MSW) is an extremely available and organically bound carbon source. Its annual generation as of 2016 was approximately 1.3 billion tonnes which is estimated to rise to 2.2 billion tonnes by 2025 (Sadef et al., 2016).

In this manner, through the incorporation of proper conversion technologies by adopting the circular bio-economy, biorefinery could be proved as an eco-sustainable framework which could efficiently generate multifarious bioenergy products by using various biomass feedstocks. Thereby, increased responsiveness of circular bio-economy via highlighting and holistically addressing the social, environmental, and economic aspects of diverse industrial sectors, biorefineries could act as a strategic tool for effective understanding management of circular bio-economy (CBE) with respect to greenhouse gas emissions. For example, in the case of waste biorefinery, such a circular bio-economy strategy could represent a reduced carbon economy by dropping the footprints of greenhouse gases (GHG), as well as it could support and hold great prospects for global eco-sustainable development (Ubando et al., 2020). Various biorefinery models are represented in Table 2.

## 5 Biorefinery Framework for Adapting Circular Bio-economy

Biorefinery constitutes conversion platforms like thermochemical, biological, chemical, and mechanical conversions (Ubando et al., 2020). Thereby, it is the infrastructure facility where these several transformation technologies including microbial growth stages have been integrated for efficient production of sustainable bioproduct streams like bioenergy, other valued products, etc. In the circular bio-economy (CBE), the role of the biorefinery concept is represented in Fig. 3.

The conversion platforms could facilitate the suitable conversion of different biomass feedstock to varied primary/secondary bioenergy products (Ubando et al., 2020). This framework and the biorefinery concept are represented in Fig. 4.

Sustainable bioenergy production and other valuable by-products using waste could be achieved with biorefinery concept-related studies on different types of waste including food waste, lignocellulosic waste, paper waste and municipal solid waste, and manure, which have been successfully carried out (Ubando et al., 2020) (Table 3).

## 6 Sustainability Assessment of Biorefineries

Biorefinery performance could be recorded in terms of its economic valuation related to net current value and other temporal familiar approaches, along with environmental evaluation via life cycle assessment. However, maximum studies have been

**Table 2** Methodology for assessment of biorefinery sustainability

| Biorefinery | The rationale for sustainable performance (Index/factor) | Assessment method |
|---|---|---|
| Dry wood–lignocellulosic waste | Indicator of eco-efficiency | Life cycle assessment (LCA) |
| Food waste | Energy consumption and recovery, nutrients release (eutrophication and acidification), total income per ton, total capital investment, production and operational cost, ratios of revenue–profitability, return on investment, payback period, market values, etc. | Life cycle assessment and life cycle cost, techno-economic analysis, profitability analysis, etc. |
| Glycerol waste | Potential of global warming, eco-indicator, total investment cost, capital cost, annualized net profit, payout time, cumulative energy demand (CED), etc. | Techno-economic analysis |
| Municipal solid waste | Global warming, human toxicity, ecotoxicity, nutrient release, fossil energy saving, cost of production, capital cost, value on processing, etc. | Life cycle assessment, process integration, economic value analysis |
| Solid waste of olive mill | Internal rate of return (RoR), net present value, annualized net profit, payback period, etc. | Economic assessment |
| Seaweed–algal | Climate change, marine eutrophication, CED, ecotoxicity, human toxicity, etc. | Life cycle assessment |
| Slag waste | Greenhouse gas emissions, environmental and social innovations, solid residues, process and production efficacy, transport, management and reporting, leadership and policy, legal aspects, location, supply chain, labour practices, training, skills, health, safety, etc. | Environmental–social sustainability assessment |
| Sugar mill | Consumption of fossil fuel, carbon-ecological footprint, water use, agro-industrial yield, production cost, product diversification, human development, etc. | Analytic hierarchy process (AHP) |

(continued)

**Table 2** (continued)

| Biorefinery | The rationale for sustainable performance (Index/factor) | Assessment method |
|---|---|---|
| Sugar beet pulp–lignocellulosic waste | Global warming potential, abiotic depletion, eutrophication, acidification, ozone layer depletion, human–ecotoxicity, photochemical oxidation, etc. | Life cycle assessment |
| Sugarcane–lignocellulosic waste | Payback period, net present value, fixed capital, manufacturing cost, after-tax rate of return (RoR), break-even price, etc. | Techno-economic assessment (TEA) |
| Wastewater | Climate change, resources, production cost, ecosystem quality, human health, etc. | Life cycle assessment (LCA), Techno-economic assessment (TEA), dynamic simulation |

Adapted and modified from, Ubando et al. (2020)

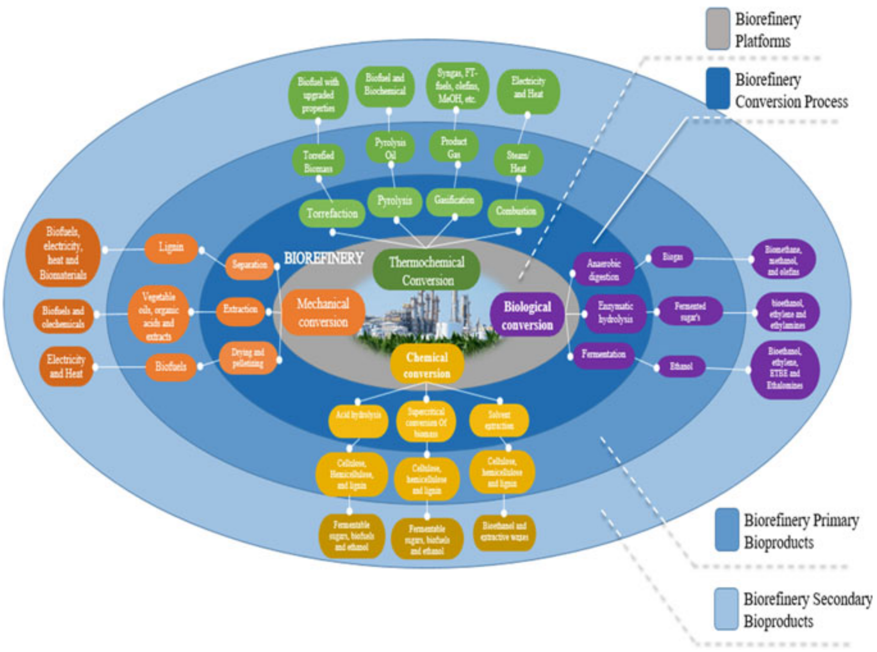


**Fig. 3** Biorefinery concept in circular bio-economy. Adapted and redrawn from, Ubando et al. (2020)

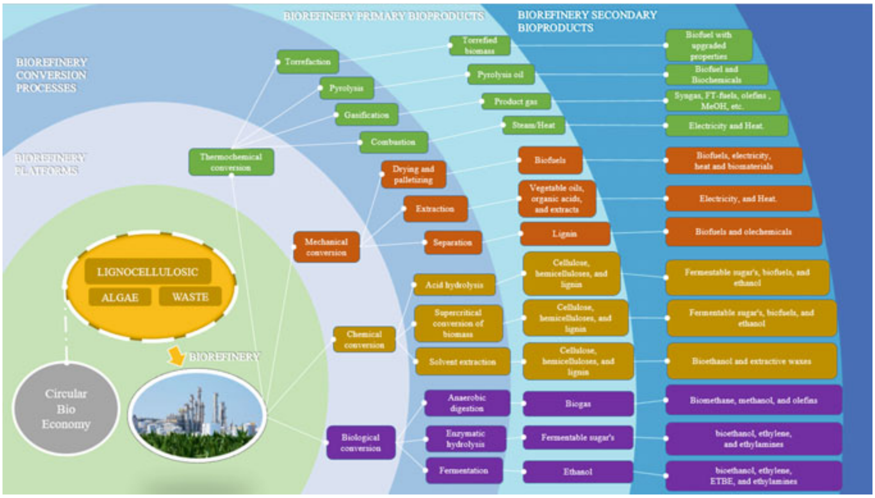


**Fig. 4** Biorefinery framework w.r.t. circular bio-economy. Adapted and redrawn from, Ubando et al. (2020)

exclusively scrutinized with single criterion, i.e., economic/environmental, in which the possible integrated effects of multiple criteria have been frequently ignored (Tuazon & Gnansounou, 2017). The assessment of biorefineries for sustainability can be properly evaluated using the triple bottom line framework (Tuazon et al., 2013) as represented in Fig. 5 (Table 4).

## 7 Challenges Related to Adopt Circular Bio-economy (CBE) for Biorefinery Concepts

- Although cascading utilization could upturn the efficient use of resources, direct linking for reducing the release of greenhouse gas emission is still complex.
- Intermittently, although reuse of material at first stage is inefficient for a comprehensive sustainability assessment of a cascade, a full life cycle assessment is essential.
- Along cascade, products could accumulate any toxic/critical substances, and they might be barriers for further recycling/even incineration.
- Implementing the circular bio-economy in practice could be a challenge because it requires perfect foresight as well as cooperation across the value chains.
- The benefits of circular bio-economy (CBE) strategies still have to be proven in practice as sometimes they could be case specific.
- Although utilization of biomass use in electricity sector promises the highest GHG-mitigation potential after substituting coal, other renewables like solar and

**Table 3** Biorefineries and circular bio-economy

| Type of biorefinery and biomass used | Strategy | Technique | Location and regional sensitivity (Yes/No) |
|---|---|---|---|
| Industrial and agricultural wastes | Extraction/processing using either solvents, microwave, ultrasonication (US), and supercritical fluid (SCF) | Integrated extraction and purification, utilizing renewable materials from different origins | Not available, No |
| Agro-based Organic manure | Aerobic/anaerobic, thermochemical processes | Recycling of manure for multifunctional utilizations | China, No |
| Microalgae and algal–seaweed | Valuable by-product extraction, biosorption, anaerobic digestion | Integrated biomass conversion processes to seaweed biorefinery<br>Reintroduction of biorefinery waste/residues in 'industry chain' | Ireland, Yes |
| | Anaerobic co-digestion | Use of rich carbon crop residues and algal waste | China, Yes |
| | Extraction by solvent/ultrasound (US)/microwave, supercritical fluids (SCF), and bioconversion via fermentation/trans-esterification, etc. | Exploration of biodiversity potentials of microalgae, process optimization of available resources | Mexico, Yes |
| | Extraction of bioproducts/biocompounds, hydrolysis, anaerobic digestion, fermentation, liquefaction, combustion, gasification, pyrolysis, etc. | Fractionation and recovery of valuable products, their utilization in multistage cascade processes | Not specified, Yes |
| Food–food supply chain waste | Anaerobic digestion, composting, animal feeding, etc. | Reuse, recycle, and use by-products | Not specified, No |
| Food–fruits–vegetable waste | Acidogenesis, methanogenesis, solventogenesis fermentation, and bio-electrogenesis | Facilitating bioprocesses which yield several bioproducts which can be used for biomass valorization | Not specified, No |

(continued)

**Table 3** (continued)

| Type of biorefinery and biomass used | Strategy | Technique | Location and regional sensitivity (Yes/No) |
|---|---|---|---|
| Food–rapeseed oil | Extraction of bioactive compounds by high-voltage electrical discharge/microwave-assisted/pulse-electric field/ solvent, enzyme, etc. | Isolation of bioactive compounds from a by-product of less economic importance | India, Canada, China, Europe, Yes |
| Glycerol waste | Combustion, gasification, hydro-genolysis, selective oxidation, epoxidation, pyrolysis, trans-esterification, selective etherification, polymerization, dehydration, carboxylation, chemo-catalytic technologies, etc. | Synthesis of high-valued products, energetic co-valorization, industrial symbiosis, conventional/renewable fuels for combined heat, power generation, etc. | Hong Kong, Greece, Yes |
| Waste of lignocellulosic-agro residue, dairy, dry wood, etc. | Microbe-assisted conversion, cogeneration systems, enzymatic hydrolysis, fermentation, recovery of organic compounds like acetic acid, furfural, etc. | Integrated processes centred on product fractionation of biomass as well as a combination of lignocellulosic residues and other waste substrates into first-generation ethanol plants | USA, Brazil, Yes |
| Lignocellulosic–paper waste–newsprint | Acid/enzymatic hydrolysis, ion cell-F process, alkaline polyol treatment | Cellulose nanofiber films are comprised of composite reinforcement in building materials, packaging, electronic components, biofuel, low refined waste cellulosic materials conversion to high-valued man-made cellulosic fibre, etc. | Europe, Yes |

(continued)

**Table 3** (continued)

| Type of biorefinery and biomass used | Strategy | Technique | Location and regional sensitivity (Yes/No) |
|---|---|---|---|
| Sugarcane bagasse, sugar beet molasses-sugar beet pulp | Solid-state fermentation, material refining, extraction, hydrolysis, bioconversion | Bioproduction of aromatic compounds using agro-industrial wastes/residues, fractionation, bioconversion to high-valued products | Not mentioned, Yes |
| Lignocellulosic waste | Microbial enzymatic treatment | Value addition of lignocellulosic wastes by integration with biorefinery framework | Not available, No |
| Municipal kitchen, municipal solid waste | Fermentation and trans-esterification, solid-state fermentation, enzymatic hydrolysis, and microbial bioconversion, gasification and pyrolysis | Biofuel production processes, production of high-value-added compounds, fuels and chemicals, replacement to new raw materials providing services concerning fuels, chemicals, fertilizers, etc. | Africa, America, Asia, Europe, Yes |
| Sludge/organic wastes | Microbe-derived electrochemical processes | Conversion of waste carbon materials into valued products | Not specified, No |
| Stream-general waste/protein waste | Pyrolysis, gasification, combustion, refuse derived fuel (RDF), fermentation, anaerobic digestion, enzymatic conversion, plasma arc gasification, hydrolysis, liquefaction biotransformation, metabolic engineering | Production of energy, high-valued products, bulk chemicals | Not specified, No |
| Waste of wineries | Enzyme-based treatment, extraction via microwave, ultrasound (US), supercritical $CO_2$, high-voltage electrical discharges, sub/supercritical fluids | Separation and recovery of valued components | Italy, Yes |

Adapted and modified from, Ubando et al. (2020)

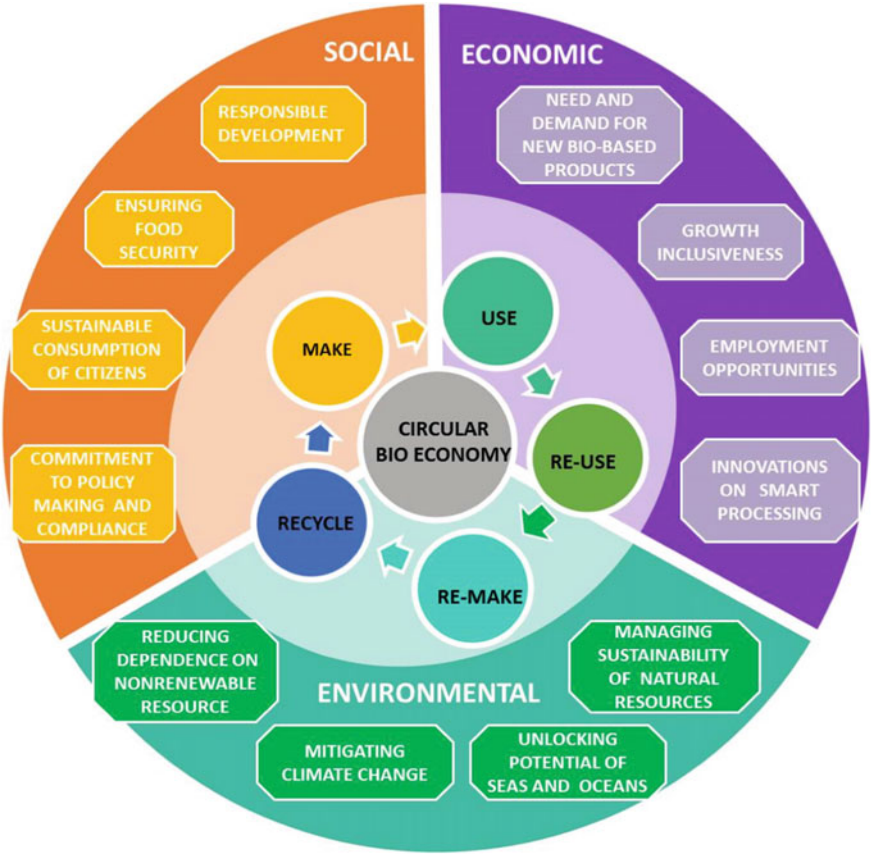


**Fig. 5** Circular bio-economy (CBE) and triple bottom line assessment tool. Adapted and redrawn from, Ubando et al. (2020)

wind could reache higher shares in the future energy mix and such mitigation potential might be diminished over the time.

## 8 Further Recommendations for Adoption of Biorefineries in Circular Bio-economy (CBE)

- Integrated assessment of circular bio-economy related to broad economy is necessary to evaluate the clustered influences of various biomass uses and significant advantages of various end-of-life strategies.
- Successful alternatives to eco-sustainable CBE, consumers, investors, as well as architects and engineers should be involved and provided with the guidance towards the effective implementation of CBE principles.

**Table 4** Strengths and weaknesses of the biorefineries w.r.t. circular bio-economy

| Type of biorefinery | Strengths | Weaknesses |
|---|---|---|
| Lignocellulosic materials like dry wood waste/sugarcane bagasse, sugar beet molasses | It is indicator for sustainability w.r.t. monetary benefit which permits the merging of economic growth and environmental protection, it could exhibit positive impact on socio-economic development related to diversification of product as well as profitability, and it could have potential to reduce the investment risks, environmental impacts in comparison with stand-alone systems | There might be issues related to pretreatment of biomass also requirement of process energy, it might require proper approaches for identification of degree of sustainability of the complete system<br>Most of the times, the economic feasibility might be dependent on the co-products prices |
| Food–food–fruits–vegetable waste supply chain | Cascading utilization of resources through different stages like reuse, recycling, and bioenergy conversion<br>Transformation of biomass feedstock into high-valued products and energy by zero-waste generation | There might be inconsistency with respect to material quality, less analysis at industrial scale, most of the time there might be inefficient biogas production and utilization due to collection, monitoring, and process control |
| Municipal kitchen solid waste/dry solid waste | It generates economy by valorization of such wastes showing ability to become sustainable on its own, planned biorefinery investment. It would have a significant impact on the local and regional economy | There might be feedstock impurities, lack of management and reporting approaches related to sustainability, monitoring of greenhouse gas emissions (GHG), life cycle assessment, and awareness of circularity |
| Stream-general wastewater/protein waste | It could support pollution control, and it could provide manifold benefits including synthesis of new products as well as fossil-free processes | There might be less life cycle thinking and awareness of circularity |

Adapted and modified from, Ubando et al. (2020)

- Policies related to research programs should be focused on product design and end-of-life strategies for various bioproducts.
- Policies increasing the carbon dioxide price should bring up the CBE by increasing the economic effectiveness in respect of resource-efficiency measures along with utilizing the wastes and residues instead of primary resources.
- Clear policy incentives to optimize related emission mitigation potential of CBE are necessary in such way that it should not only adapt this economy as a whole

but should also focus on utilization of biomass and cascading pathways which could also exhibit the all-out emission reduction potential.

- There is need to intensify and increase market opportunities along with preferment of reuse, recycle, and application of corporate social responsibility (CSR) related to businesses and prominence on product life cycle as well as circularity in the course of development of new products and services, business models, and corporations.

In this way, circular bio-economy has remarkable potential to improve the eco-sustainability w.r.t. biorefinery concepts if the practitioners would support the eco-sustainable development by empowering collaboration between the stakeholders along and across the supply chains; by fostering bio-based product design which could facilitate durability, reuse, repair, recycling/biodegradability; by promoting the utilization of residues and wastes as resource; and by strengthening the cooperation with waste management sector for ensuring that bio-based products could be integrated in the schemes w.r.t. collection, separation, recycling, and composting.

## 9 Conclusion

Worldwide, sustainable green economy programs and strategies are booming. Adaptation of circular bio-economy comprises expanding the usage of modern biorefineries, based on emerging concepts and technologies. The technological development and installation of new biorefineries in line with such new concept could be used as indicators for promotion and eco-sustainable development. In this context, with the strategic implementation of biorefineries in different industrial sectors, the effectiveness related to circular bio-economy (CBE) should be quantitated through different sustainability assessment strategies to hold great prospective for sustainable green world.

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# Biofuels as Economic Security for the Poor

**Sunzida Sultana, Abdullah An Nur, Saleha Khan, Ranga Rao Ambati, and Ravishankar Gokare Aswathanarayana**

## 1 Introduction

The renewable biofuels invention has received substantial attention worldwide over the last decades as a low carbon alternative to fossil fuel due to its biodegradability and ecofriendly nature (2015). In recent years, fossil fuels burned for transport, electricity and heat by human activity increased the amount of carbon dioxide in the global context, increasing the production of renewable biofuel represents the great possibility of substitution of fossil fuel in many developed and developing countries ($CO_2$) in the atmosphere leading to global warming and climate change. Earth's non-renewable fossil fuel was viewed as a prominent part of the industrial, agricultural and transportation sectors in the past which caused harm to the environment. The consumption of fossil fuels promotes the emission of greenhouse gases (GHGs), air contamination and water scarcity. According to International Energy Agency, in the developed countries, biofuel production has enhanced by over 10% between 2013 and 2019, compared to developing countries. On the other hand, developing countries such as Argentina, Brazil, China, India, the Philippines, Malaysia, and Thailand illustrate half of the increment to biofuel production (Fig. 1) (Kang et al.,

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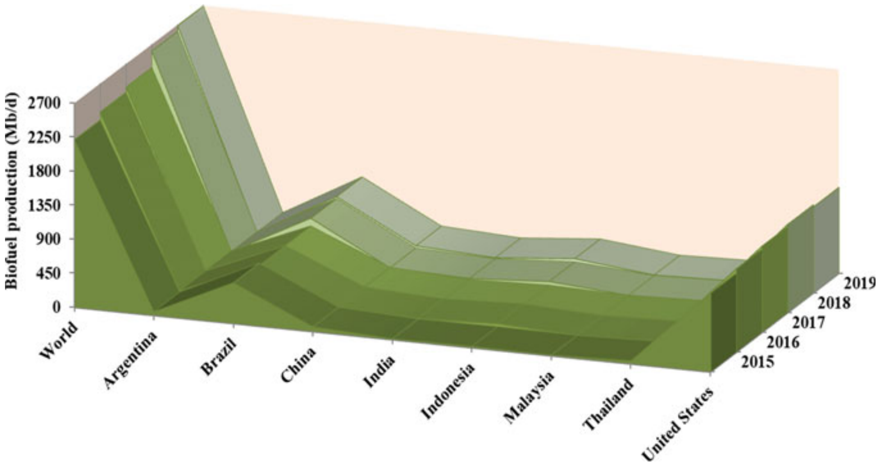


**Fig. 1** Total biofuel production (Mb/d). (data is taken from U.S. Energy Information Administration, 2019)

2015; Mandegari et al., 2019). The utilization of modern renewable biofuels is crucial in improving environmental, social and economic sustainability.

The viability and competency of renewable biofuel depends on the sustainable production of biomass. The edible and non-edible sources are two types of natural sources for influencing the biofuel production. First-generation biofuel competes with food crops as it is derived from edible sources, including sugar- and starch-rich crops, animal fat and vegetable oils. However, second- and third-generation biofuels are manufactured from non-edible sources like agricultural and forest residues, industrial wastes, municipal solid wastes and microalgae that are not competitive with food crops. Recently, the demand for biofuels production has increased significantly as it assures economic security through poverty alleviation and rural development.

In 2019, around 1.3 billion people in 101 countries were living in poverty and most of them were economically deprived. Economic deprivation means a lack of clean water and air, land, forestry products, food stock, roads, transports, markets, communication systems, education, nutrition, employment and secure job entrepreneurial opportunities (Sida, 2017). In every country, poor people are struggling to meet fundamental human needs such as food needs, health, lighting, mobility, space comfort and communication via the services of bioenergy. The biofuel sector has been perceived as pivotal to lessen the economic instability of people through a dynamic relationship between economic productivity and the continuation of biofuel consumption. Sustainable development is directly linked with renewable biofuel through its influence on economic growth and human development (Asumadu-Sarkodie & Owusu, 2016b). Therefore, economic globalization of biofuel is perceived to be the driver of economic growth, especially in developing countries, which will be influenced by the improvement in technologies, production efficiencies, and decreased costs of production.

In several countries, economic insecurity and poverty are condensed in rural areas. Most of the producers of biofuel crops are poor and live in rural areas. They are also handicapped by inadequate skills and knowledge. Moreover the economic instability and lack of access to investments will curb them to take up the project in a big way. However enhanced funding for infrasturcture, skill empowerment would add tremendous value to biofuel industry, thereby enhancing the feedstock production. Moreover, women are expected to play a big role in feedstock production. The substitution of imported transport oil, for example petroleum, with locally produced biofuels plays an important role in reducing relatively higher oil prices and transportation costs. Fortunately, adoption of renewable biofuels are also lowering the costs of electricity and gas in the rural households. With increasing biofuels generation, has influenced women empowerment in rural areas. It has also resulted in higher land value, direct and indirect job opportunity, minimization of costly oil import with some degree of reduction in the cost of fuel and electricity costs in many countries.

The direct and indirect benefits to economy and ecology of the region warrants intensive research and development on various facets of production of biofuels, hence this chapter attempts to focus on the issues related to biofuel production, sustainable land management, water security, technical and institutional innovations with examples of components that accelerates economic security and reduces poverty.

## 2 Biofuels Generation as Economic Security for the Poor

Biofuels are mainly renewable, biodegradable, carbon–neutral and environmentally imperishable fuels alternative to conventional fossil fuel. Biofuel production is directly or indirectly dependent on the biomass from edible and non-edible sources. Diversified edible and non-edible sources of biofuel are largely coupled with the necessities of rural poor's daily needs for nourishment, fuel and shelter. Edible sources of biofuel are sugar-rich crops, starch-rich crops, oilseed crops, animal fat, pure plant oils and vegetable oils. Producing biofuel from edible sources has raised concerns owing to their conflict with food crops. Conversely, non-edible sources of biofuel include microalgae, photosynthesizing microorganisms, agricultural wastes, food industry wastes and municipal wastes. Hence, the non-edible sources are proposed as viable feedstock of biofuel production process.

Depending on feedstock type, conversion process, innovative technologies and utilization, biofuels are categories into three generation-types (Table 1). Lately, extensive research on fourth-generation biofuels has been the focus of considerable interest genetically modified or engineered feedstock with genomically synthesized microorganisms. However, the development of fourth-generation biofuels is in its infancy and has not gained support due to the lack of globalized-regulatory considerations.

**Table 1** Classification of biofuels, their benefits and limitations (data is taken from Doshi, 2017; Fatma et al., 2018)

| Biofuel class | Feedstock of biofuel production | Benefits | Limitations |
|---|---|---|---|
| *Conventional biofuels* | | | |
| First generation | Corn, sugarcane molasses (ethanol) soybean, palm oil, rapeseed, sunflower oil (biodiesel) | Reliable, locally distributed price stability, less expensive, non-toxic, etc | Tax credits on production, mostly criticized, emits $CO_2$, less fertile soil, etc |
| Second generation | Forest residues, sugarcane bagasse (ethanol)<br>Jatropha (biodiesel) | Reduce $CO_2$ emission, biodegradable, better waste utilization, reliable than the first generation, employment generation, etc | Expensive, complex process, increase Nox gases, lower energy con-tent, stability concerns, food–fuel competition, etc |
| *Alternative biofuels* | | | |
| Third generation | Microalgae (ethanol, biodiesel) | Relatively cheap, high biomass productivity, low fouling, easy maintenance, less prone to contamination | Scalability problem, need maximum light exposure, periodic cleaning, temperature maintenance, high initial investment cost, high-energy usage |

## 2.1 *Rural Economic Stability Through First-Generation Biofuels*

Developing countries like Africa, Argentina, Bulgaria, China and India obtain bioethanol from corn; while Brazil, Bolivia, Mexico and Uruguay manufacture bioethanol from sugarcane. In addition, Argentina, Brazil, Indonesia and Uruguay produce biodiesel from palm and soybean oil. In conformity with the latest official statistics (Renewable Energy Policy Network for the twenty-first century, 2017), perennial global biofuels production outstretched 4.9 billion litres of hydrogenated vegetable oils (HVO), 30 billion litres of biodiesel and 98 billion litres of ethanol. Giovannetti and Ticci (2016) and Bórawski et al. (2019) scrutinized the indicators of biofuel demand world wide. The feedstock requirements in biofuels production are varied pursuant to geographical zone (Table 2).

Nowadays, maximum biofuel industries produce first-generation biofuels which depend on agro-based feedstocks (Fig. 2). Those industries provide a number of direct and indirect work opportunities and economic security for eradicating poverty from the rural poor people. Even some industries take lease of agricultural and marginal lands for higher biofuel-related crop production, and by this, rural poor’s receive

**Table 2** Biofuels feedstock and their production (data is taken from Gomez et al., 2008 and U.S. Energy Information Administration, 2019)

| Country | Biofuel feedstock | Fuel ethanol(Mb/d) in 2019 | Biomass-based diesel(Mb/d) in 2019 |
|---|---|---|---|
| Argentina | Soybean, corn, sugarcane and vegetable oils | 19 | 43 |
| Brazil | Sugarcane, cassava, molasses, castor, sunflower, soybean, palm, wheat, rice and corn | 541 | 100 |
| Bulgaria | Soybean, rapeseed, sunflower seeds and wheat corn | 0.3 | 3.1 |
| China | Corn, rice, wheat and cassava | 74 | 21 |
| India | Sugarcane, sugar beet, sweet sorghum, corn, cassava and vegetable oils | 41 | 3.3 |
| Indonesia | Palm oil, sugarcane, and cassava | 0 | 138 |
| Turkey | Sugar beets, corn and wheat | 1.7 | 2.4 |

adequate rental values of land that secure their economic stability in the society through poverty reduction.

## *2.2 Consequences of Second-Generation Biofuel in Economic Safety and Poor*

The second-generation (2G) biofuels are liquid and gaseous fuels from non-food feedstocks such as lignocellulosic biomass. Typical lignocellulosic biomass is yielded from agricultural by-products (e.g. rice straw, husks, corn stover, sugarcane bagasse and stalk), forestry residues (e.g. treetops, branches and thinning), perennial grasses (e.g. Switchgrass and Miscanthus), short rotation coppices (e.g. poplar or willow), animal wastes and municipal solid wastes (MSW) (Fig. 3). Among various non-food feedstocks, rice straw, a by-product of rice production is the most profuse substantial lignocellulosic materials in the world that can be easily changed into biofuels. Saini et al. (2015) mentioned that Asia alone produces over 90% of the annual global production of rice straw that is nearly 731 million tonnes. Second-generation biofuel production from perennial crops such as reed canary grass (*Phalaris arundinaceae*), switchgrass (*Panicum virgatum*) and miscanthus (*Miscanthus sinensis*) has received considerable attention in Europe and North America.

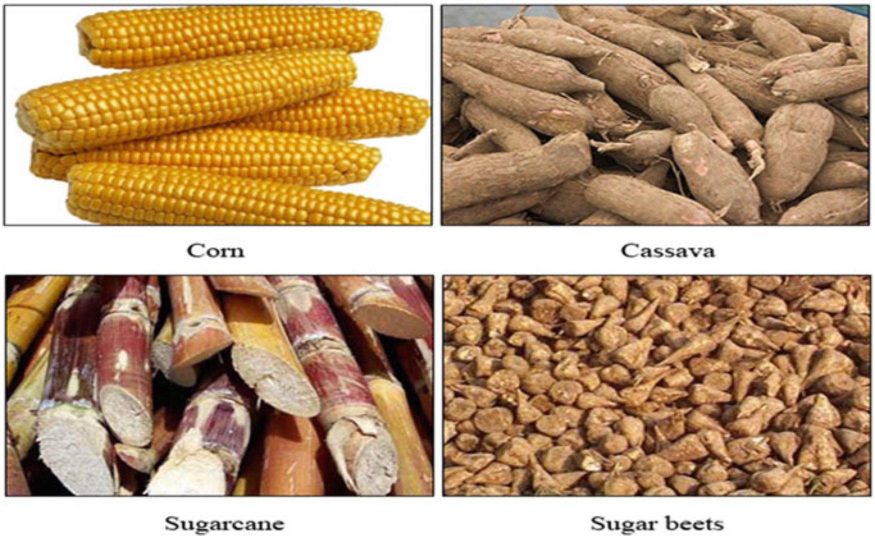


**Fig. 2** Feedstock's of first-generation biofuel (photo is taken from bioenergy research group, University of Hawaii)

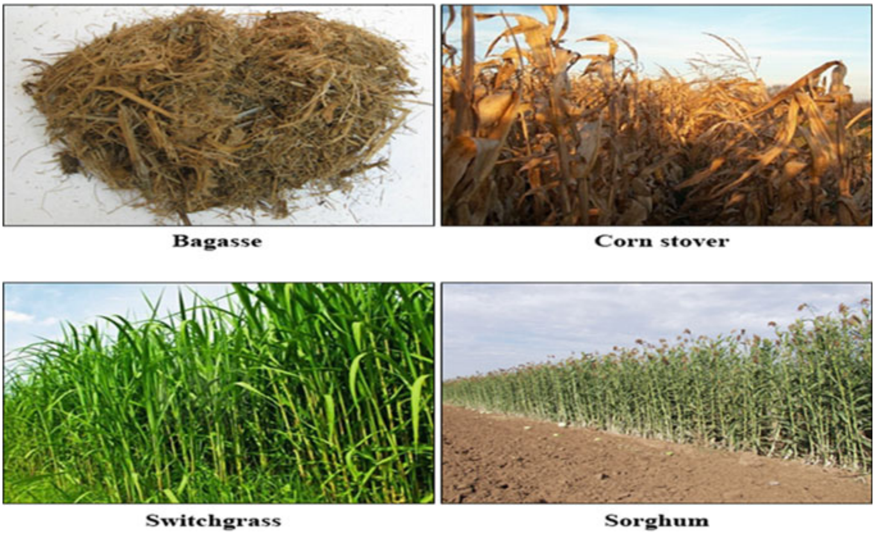


**Fig. 3** Feedstock's of second-generation biofuel (photo is taken from Bioenergy research group—University of Hawaii)

Producing biofuels via traditional processing technologies from feedstocks under conditions of hydric stress (e.g. Jatropha) as second-generation biofuels has gained attention. However, there is resistance to cultivation of Jatropha in comparison to some other high value drought resistant crops. However, Jatropha cultivation was adopted due to ease of cultivation, before it was realized that the labor intensive harvesting became a issue. Here the oil from Jatropha seeds were extracted and converted to biodiesel thorugh trans esterification process. In case of lignocellulosic biomass, two distinct processing routes were adopted. Conversion of lignocellulosic biomass to sugars through enzymatic processes and subsequent conversion of sugars to bioethanol by using microorganisms. Elsewhere, the thermochemical route consists of two separate processes: gasification to make synthesis gas and pyrolysis to make a bio-oil from which long carbon chain biofuels are derived, for use as aviation fuel.

Second-generation biofuel has great implications for economic productivity and impoverishment. Sustainable economic growth requires safe and procurable resources for biofuel generation. Lignocellulosic materials are the most inexpensive and plentiful non-food materials available from plants that are non-competitive in poor people's food security and economic security. In the near future, lignocellulose-based second-generation biofuel production, is likely to make an impact on rural poor through supplementary income generation.

## 2.3 *Third-Generation Biofuel's Interaction with Poor People's Economy*

Biofuels comprised of algae and other photosynthesizing microorganisms are named the third-generation (3G) biofuels that usually do not clash with human food chains and land usage, as they grow in aqueous media. Higher growths and exceptional biodiversity of microalgal feedstocks with a potential to produce high lipid content make it attractive for generation of biofuels. The biofuels that are generated from microalgae involves bioethanol, biodiesel, bio-hydrogen, bio-methane, bio-oil and others (Hossain et al., 2019a, 2019b). Conventional transesterification or hydro-treatment of algal oil is done to produce biodiesel from microalgae. Several commonly known microalgal species have been widely researched in large-scale applications. Their type and description with elaborate information of selected species, suitable growth conditions, availability and cellular specifications have been provided in Table 3.

Microalgae require need relatively less water for yield of biomass and also do not compete with areable land otherwise used for agriculture. Ecologically microalgae grow and accumulate nutrients from freshwater, brackish water, salt water, industrial and municipal waste dumping areas. Various cost-effective, innovative microalgal cultivation systems like open systems, suspended microalgae PBRs (photobioreactor)

**Table 3** Some examples of the composition of microalgae species expressed on a dry matter basis (Adopted from Dragone et al., 2011; Hossain et al., 2019a, 2019b)

| Microalgae name | Protein (%) | Carbohydrate (%) | Lipid (%) | Description in brief |
|---|---|---|---|---|
| *Chlamydomonas reinhardtii* | 48 | 17 | 21 | Genetically modified by sex-cross, it contains a high amount of carbohydrate, lipid and protein in the cell wall |
| *Chlorella pyrenoidosa* | 57 | 26 | 2 | Unicellular green microalgae, source availability of tropical water with enough solar light |
| *Spirulina platensis* | 42–63 | 8–14 | 4–11 | Spiral-shaped multi-cellular microalgae (with no true nucleus), freshwater habitat, contains lipopolysaccharides and peptidoglycan (carbohydrate components) in the cell wall, as well as cyanophycean and starch, are the main carbohydrate storage products |
| *Chlorella vulgaris* | 41–58 | 12–17 | 10–22 | Spherical-shaped, single cellular (with nucleus) microalgae, grows in both fresh and marine water with adequate sunlight, contains cellulose and hemicelluloses (carbohydrate components) in the cell wall, and starch is the main carbohydrate storage product |
| *Botryococcus braunii* | 40 | 2 | 33 | Green microalgae, shape type pyramidal, source availability of tropical and oligotrophic freshwater such as lakes, ponds, estuaries |

(continued)

**Table 3** (continued)

| Microalgae name | Protein (%) | Carbohydrate (%) | Lipid (%) | Description in brief |
|---|---|---|---|---|
| *Spirogyra* sp. | 6–20 | 33–64 | 11–21 | Shape type spiral, source availability in a usually moist environment, marine and freshwater sources, grown randomly in tropical areas where sunlight is available sufficiently |

**Fig. 4** Green algal cultivation pond in University of Turku, Finland used for biofuel production (photo is taken from Design News, 17 May 2018)

and algae biofilm PBRs (horizontal static biofilm systems and vertical static biofilm systems) are now used for biomass production for conversion to biofuels.

Microalgae utilization for biofuel production is highly desirable in today's world because of its high-energy efficiency and environment-friendly nature. In Bangladesh, biofuels from high lipid-containing microalgae could be a potential alternate fuel. For manufacturing economically viable and sustainable biofuel from microalgae, the development of an innovative mass culture technique is the need of the hour (Fig. 4).

## 3 Influence of Biofuels in Economic Security for the Poor

A sustainable and cost effective bioenergy supply is necessary for all economies. Biofuel production are ecofriendly and economically feasible. At present, the demand for biofuels development establishes biofuel industries, creates gender empowerment, improves land rental values, increases income by employment generation, minimizes oil price and transportation costs, reduces electricity cost and gas cost to indemnify the economy and rural poor.

### *3.1 Industry Establishment*

Industrial biofuels production systems are manifested to be smaller and more decentralized than others. Those decentralized processing systems are efficient in alleviation of rural poverty by creating year-round employment. The contribution of the biofuel production industry to rural development depends on whether or not the rural economy can provide adequate feedstock to biofuel producing factories. The most commonly used feedstock for biofuels production is sugarcane, sugar beet, sunflower, soybean, palm, wheat, rapeseed, sweet sorghum, corn, cassava and vegetable oils, etc. Producers of the biofuel industry can possibly receive reasonable profits by partnering with rural society in feedstock production, where both stand to benefit.

The Mozambiquan government allows bioethanol production from sugarcane as the main feedstock among other feedstocks by the National Biofuel Policy Strategy due to its lower production costs and energy efficiency. The Centro de Estudos de Políticas e Programas Agroalimentares (CEPPAG) connects community and commercial sugarcanes yield to raise 90.5 and 92.3 t/ha in 2016/2017 (CEPPAG, 2016). Power and heat generation from bagasse (a by-product of sugarcane) make the sugarcane industry more competitive compared to the sugar beet industry (Goldemberg et al., 2008).

The extensive development in the biofuels production industry maximizes the employment generation opportunities through assuring economy and rural development, particularly at the regional level (Fig. 5). Thurlow et al. (2016) found that investments in biofuels development accelerated economic growth and poverty alleviation. The biofuels production industry employs a wide range of skilled and non-skilled labours in a variety of sectors. Skilled labours are needed in processing plants, feedstocks cultivation, plant operations and sales. In the meantime, many biofuel industrial works are done by non-skilled labour, and those non-skilled manual labours are aided by offering occupational education and other employment opportunities. These patterns of employment from biofuels sectors are economically useful for uneducated rural people. In developing countries such as Argentina, Brazil, India, Indonesia, Thailand, the Middle East and North Africa highest movement of rural unskilled labour than urban unskilled labour are noticeable towards the higher biofuel expansion. A bioethanol industry in Mozambique is accounted to create directly around 56000 jobs through feedstock and processing activities by 2025 (Hartley et al., 2019). According to International Renewable Energy Agency (IRENA), the US ethanol industry supports over 200,000 employees by providing direct and indirect jobs (Energy Futures Initiative, 2019). The US Energy Employment Report

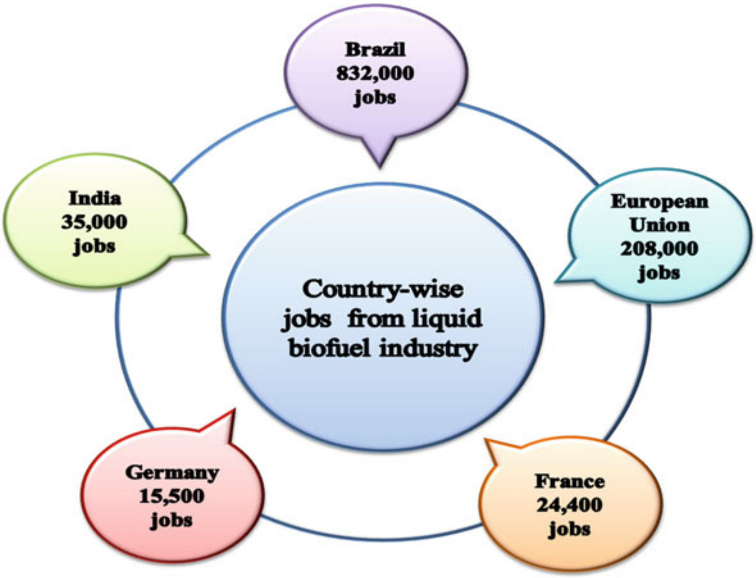


**Fig. 5** Top employment producing countries through liquid biofuel industry (data is taken from renewable energy and jobs annual Review 2019)

(USEER) also found that the advanced biofuels industries employ nearly 19,000 people (Energy Futures Initiative, 2019).

## *3.2 Gender Empowerment*

Gender empowerment is the other name for women empowerment that means empowering women to participate in all aspects of life such as stronger social, political and economic improvements. Renewable biofuel energy has positively influenced women empowerment in rural communities by means of potentially reducing drugery in the kitchen, offering them other occupational advantages.

Evidence from the USA and Canada reveals the bioenergy sector is more gender mosaic compared to the fossil fuel industry (Emmons Allison et al., 2019). However, the gender diversification in bioenergy companies is improving better business performance (Pearl-Martinez & Stephens, 2016). Traditionally, women and children were involved in fuelwood gathering and cooking in Bangladesh and India that reduced women's activities from doing other works and lessened school enrolment and education of children. However, the adoption of latest biomass based biofuel technologies is providing opportunities for female labour to ascertain gender empowerment and economic security in rural communities (Fig. 6).


**Fig. 6** Participation and empowerment of women in biofuel (photo is taken from Karlsson & Banda, 2009). **A** Women extracting jatropha oil in Ghana, **B** women operating pedal-powered biodiesel processer in India, **C** women in Kinbhlingi making soap using glycerine, a by-product of biodiesel, **D** men and women participate in a coordination committee meeting in Nepal

## *3.3 Proper Use of Land*

The perennial or annual biofuel crops can be grown in the same land in combination with other food crops for the production of biofuel crops. Perennial plants like palm, sugarcane, switchgrass, soybean and short rotation coppices can be collected over the years in lieu of other annual crops such as rapeseed, maize or other cereals. Crop residues rely on peak crop production, and the cultivation area includes sugarcane straw, cereal (rice and wheat/barley), straw and corn stover that are potentially used for bioethanol production (Saini et al., 2015). In the USA, the generation of soybean for biodiesel needs much less pesticide and fertilizer per unit of energy production instead of maize. The residues of biofuel crops provide many benefits like supply micronutrient and soil organic matter, protect soil erosion and enhance soil structure. Cultivation of perennial lignocellulosic crops such as poplar, eucalyptus, willow or grasses in poor quality land also improves soil quality by increasing organic carbon levels and soil cover over time.

The establishment of multipurpose plantations is a common practice these days for multifarious applications such as capture carbon, pastures and production of food crops to reduce the loss of surface soil moisture and wind erosion (WEC, 2016). Nearly, two-thirds of Ghanaian agricultural land area are divided

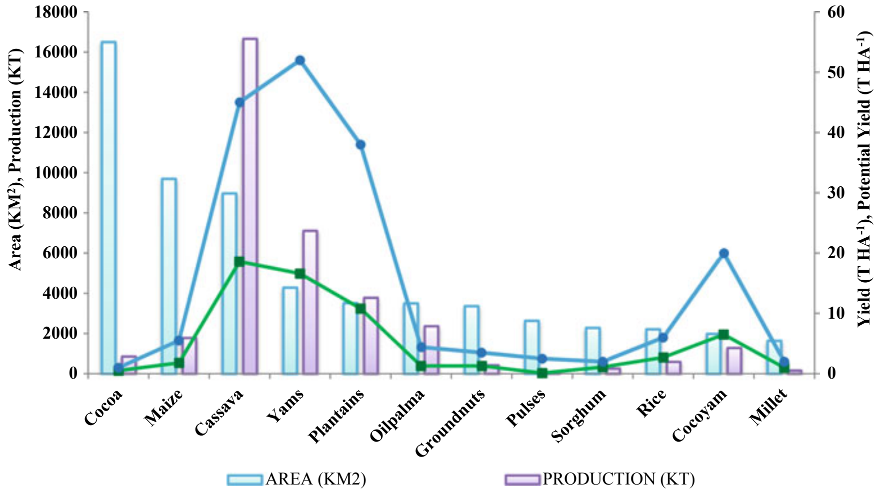


**Fig. 7** Overview of crop production and land use in Ghana (average 2012–2016) (FAO, 2016; Agriculture M.o.F.a, 2017; and G.O. Ghana, 2015). Potential yield is the yield level that is already achieved under optimal conditions in the country (Agriculture M.o.F.a, 2017)

evenly between croplands and meadows and pastures for livestock (FAO, 2016). Little intensification of the Ghanaian agricultural land creates the potential to raise biofuel growth without reducing food production or dilating arable land area (Fig. 7).

### *3.4 Reduction of Oil Price and Transportation Cost*

According to the World Energy Outlook (Energy Information Administration, 2016), the global demand for transport is likely to increase by 40% by 2035. In Organization for Economic Co-operation and Development (OECD) countries, transport contributes to 29% of carbon dioxide ($CO_2$) emissions, according to the International Energy Agency (International Energy Agency Statistics, 2016b). The devising of renewable liquid biofuels is assumed as a workable and hopeful way of eliminating $CO_2$ emissions from the transportation sector. Recently, the expansion of alternative renewable biofuels for transport is receiving worldwide attention for their carbon neutrality and cost-effectiveness. Generally, the development and utilization of biofuels for transport offer a range of socioeconomic favours in place of fossil fuels, such as reduction of GHG emissions, rural development and improvement of security supply.

Nowadays, the great majority of transports are powered by biofuels and biogases. In Brazil, corn- and sugarcane-based bioethanol are characterized by excellent energy output, thus avoiding energetic dependence from the imported oil for decades. European Union strongly suggested the usage of biofuels derived from renewable biological sources setting a clear target for 2020 that 10% of total fuel quantity used in transportation, which was achieved.

### *3.5 Minimization of Electricity and Gas Cost*

Global biofuels utilization is incessantly increasing and an important source of bioenergy for electricity generation, heating and cooking. In recent years, solid biomass has been used as fuel to process heat and generates electricity that replaces fossil fuels and minimizes the cost of energy production. Usually, solid biomass is a natural biological resource originally evolved from living matter such as plants, animal excreta and crop residues (Sansaniwal et al., 2017). During combustion, solid biomass is used in heating or food cooking and electricity production (WEC, 2016). Solid biomass includes wood, agricultural and forest residues, by-products of biological materials, waste sludge from water treatment plants and organic fraction of municipal solid waste (MSW) to produce bioenergy.

Biofuels are also converted to electricity and heat by efficient processes (Sansaniwal et al., 2017). The widely used advanced technologies for the generation of electricity and heat are combined production of heat and power (CHP), co-combustion and fluidized bed (FB) combustion. Europe and North America mainly use charcoal and wood as solid biofuels in electricity and heat creation in CHP processes (WEC, 2016). The use of biomass in electricity production is noticeable in Europe and North America that contributes more than 70% of consumption. On average, 7.6% of European energy demand had been covered, and 445 terawatt-hours (TWh) of electricity (nearly 2% of the world's electricity production) were generated by solid biomass in 2014. Germany is one of the European countries which has established biomass production facilities that provided about 49.1 TWh of energy in the same year, accounting for 8% of its electricity consumption (Strzalka et al., 2017). However use of solid biomass has been projected to benefit the Asian and African population (IRENA, 2015).

Nearly, 28 million households in Asia and Africa had adopted clean stoves by the end of 2014. High-efficiency biomass stove and biogas for cooking contribute to the displacement of traditional biomass conversion devices and, therefore, implies the reduction of the use of gas and gas cost. In sub-Saharan Africa, biomass will continue to be the premier source of bioenergy in the near future (Sansaniwal et al., 2017). The consumption of low-cost electricity and biogas progressively enhances the economic security of the rural poor.

## 4 Challenges in Biofuel Development/Recommendation

Renewable biofuel development is desired worldwide for upgrading human development for economic growth and productivity. Still, there are many challenges that impede renewable biofuel sustainability for the economic security for the poor.

- Shortage of available natural water and land resource obstructs the large-scale application of first-generation biofuel.
- The utilization of a vast portion of environmentally managed forests and agricultural land in biofuel development should be in a manner not jeopardizing the food production.
- The expensive and higher cost of biofuel production compared to fossil fuels is a matter of concern, which needs to be addressed through R&D.

Challenges of biofuel development are the primary hindrance to economic stability. The following recommendations are envisaged to sustain biofuel development goals by means of reducing poverty and achieving economic security for all the poor and future generations.

- First-generation biofuel production on a large scale needs to be stopped for their high water and land requirements.
- Increment of microalgae cultivation and harvesting to produce biofuel needs attention.
- Adoption of marginal or degraded or abandoned land in exchange for agricultural land for biofuel creation should be ensured.
- The implementation of biofuel production from municipal solid waste is necessary for environmental and public health benefits which also promotes development to wealth from wastes as a economic activity.
- New scientific research on biofuel technologies is essential because it can eliminate the risk of natural resource competition.
- Advanced technical innovation in biofuel production requires minimizing the production cost and improving biomass carbon utilization in developing countries.

## 5 Conclusions

In today's world, biofuels production is a necessity from the environmental point of view. It also supports economic activity by empowering the people especially women. The role of biofuels in sustainable development is associated with growing climate change, land and water use, human health, food security and other economic activities of rural families and communities. Research and development of biofuel industry is needed for making it competitive, attractive and easily adaptable for sustainable energy generation.

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# Circular Economy Potential of Microalgal Refinery

**G. Saranya and T. V. Ramachandra**

## 1 Introduction

Renewable energy resources are intrinsically linked to social, economic, and environmental dimensions and need to be economically viable, technically feasible, socially acceptable, and environmentally sound to achieve sustainability (Chatterjee & Rayudu, 2018). Industrialization and subsequent globalization witnessed an escalation in energy utilization, evident from the increase in the average per capita electricity consumption from 2.5 MJ $d^{-1}$ to more than 200 MJ $d^{-1}$ (Ramachandra & Hegde, 2015). Next to electricity, the major energy required is the conventional non-renewable fuels such as refined petroleum products and natural gas for mobility in the transportation sector. The global primary energy consumption is about 25,912 quadrillion Btu in petroleum (in 2019). The biomass and natural gas contribution was about 1411 and 978 quadrillion Btu. However, the fast-perishing stock of fossil resources with the escalating greenhouse gas (GHG) footprint necessitates the investigation of sustainable alternatives to meet the ever-increasing demand for energy in the transportation sector. The transition to biofuels gives the additional benefits of decarbonization, decentralized employment generation (and remediation, in the case of feedstock cultivation in wastewater), and the scope for economic viability through a circular economy in the algal refinery. Decarbonization aids in mitigating global warming and changes in the climate (Jaccard, 2006). Currently, there are numerous biofuel initiatives across the globe to reduce the reliance on petroleum

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fuel (Vlysidis et al., 2011) through decentralized local resources such as microalgae, etc. Biodiesel is one of the most promising biofuels shown to give engine performance with reduced particulate, carbon monoxide, and hydrocarbon emissions compared to conventional diesel (Graboski & McCormick, 1998). Biodiesel has been produced from triglycerides derived from terrestrial oil seeds, animal fats, or algae. Biodiesel production from vegetable oils has been increasing during the past decade. However, the amount of oil produced in a hectare area from terrestrial oil seeds is limited. In this context, microalgae-derived oil has received significant attention due to its non-conflicting nature of fuel in terms of arable land availability or food (Ribeiro et al., 2015).

Microalgae rich in carbohydrates, phycobilin, vitamins, proteins, pigments, antioxidants, bioactive compounds, and essential fatty acids offer vast potential for commercial exploitation. The biochemical composition of microalgae and biodiesel feedstock widens the scope for other bioenergy and value-added product production (Guldhe et al., 2017). There has been renewed interest in utilizing algae in various sectors, including pharmaceuticals, food, and animal feed. The main advantages of using microalgae are: (i) the most promising non-food feedstock for biofuel production; (ii) does not require arable lands with the ability to grow in degraded lands including saline waters/wastewaters; (iii) ability for an efficient fixation of $CO_2$; (iv) remediation of wastewater with the uptake of nutrients for growth; (v) algae possess the capacity to produce lipids that are 300–400 times higher than terrestrial feedstocks; (vi) carbon sequestration potential of biomass; (vii) diverse mix of energy and value-added bioproducts; (viii) livestock feed as a source of protein etc.; (ix) algal biofuel is non-toxic with no sulphur content and is exceptionally biodegradable. Remediation of wastewater through microalgal growth is gaining momentum as an economical and environmentally friendly option for wastewater treatment with biofuel production (Clarens et al., 2010). Hence, microalgae-based biofuel is emerging as an essential alternate resource to fossil fuels. However, significant challenges in microalgal biofuels are higher energy demand during (i) cultivation (upstream) and harvesting, (ii) drying, and (iii) biofuel production (downstream). Thus, employing efficient microalgae cultivation considering appropriate substrate (with biofilm inoculum) would render both cultivation and harvesting less expensive to accomplish the economic viability of microalgal biofuel. The exploitation of different microalgal components as a whole or in parts as co-exploitable products and minimizing waste production would enhance the economic viability with the potential of a circular economy. Optimal growth conditions would enhance hyper-accumulation of different bioproducts as a function of nitrogen concentration during different growth stages (Gifuni et al., 2019), as during exponential growth phase, proteins, chlorophylls and phycobiliproteins are accumulated, followed by accumulation of starch (during late exponential phase), PUFAs, TAGs, and UV protective pigments like carotenoids/astaxanthin are secreted during the stationary growth phase (triggered with nitrogen depletion). Thus, microalgae produce a plethora of products that find application in diverse industrial sectors (Chew et al., 2017).

## 2 Circular Economy Through the Microalgal Refinery

The raw material (e.g., crude petroleum) undergoes a series of production processes with a potential output of diverse energy sources (gasoline, diesel, LPG, and ethanol) and an array of complex and valuable chemicals (volatile acids, fine chemicals, detergents, pharmaceuticals, waxes, and asphalt) in the conventional refinery. Similarly, biorefineries permit renewable raw materials utilization widely at low costs to produce high-value products with inherent energy potential (Laurens et al., 2017). The biorefinery concept integrates the production of various products, and cumulative benefits prove microalgal biofuel generation sustainable by providing economic viability. Figure 1 depicts the biorefinery using aquaculture wastewater for diverse bioproduct production with an added advantage of wastewater remediation.

The biorefinery process involves valorizing microalgal biomass into a broad spectrum of value-added products and diverse energy forms (Linares et al., 2017). Microalgal biorefineries through efficient biomass processing would provide energy, polymers, food additives, nutraceuticals, bioactive compounds, co-products, etc. Processing biomass at multiple stages by targeting both primary and secondary products of commercial interest would enhance the environmental and economic benefits (Hemalatha et al., 2019) compared to product valorization.

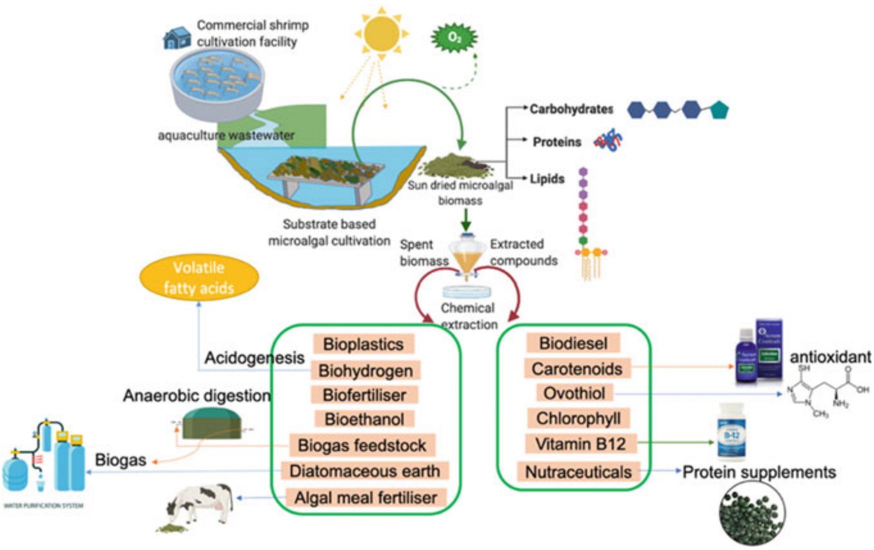


**Fig. 1** Integrated microalgal cultivation system for biodiesel with bioproducts

### 2.1 Primary Products from Microalgae

The macromolecular composition of microalgae includes (i) ash (5–17%); (ii) carbohydrates (18–46%); (iii) crude protein (18–46%); (iv) lipids (12–48%); and (v) energy (19–27 MJ/kg) (Tibbetts et al., 2015). Microalgae accumulate carbohydrates in complex forms (such as cellulose, and starch.) apart from other exocellular polysaccharides (EPS). EPS is gaining considerable attention as hygroscopic agents (in cosmetic industries), topical agents, and antioxidants (Dragone et al., 2011). EPS is useful as natural auto-flocculating agents (Marella et al., 2020), surfactants, emulsifiers, anti-tumour, anti-viral, anti-coagulant, and anti-inflammatory agents (Venkata Mohan et al., 2020). Other primary products exploitable from microalgae are pigments (chlorophyll and carotenoids such as fucoxanthin and astaxanthin), amino acids (such as alanine linoleic acid and nucleic acid), etc. Phycobiliproteins are rich sources of vitamin B1 (Mobin & Alam, 2017). Microalgae possess different carotenoids such as beta carotene, lutein, lycopene, astaxanthin, zeaxanthin, fucoxanthin, and neoxanthin diadinoxanthin, canthaxanthin, violaxanthin (Mulders et al., 2014). Carotenoid finds its application in diverse domains of human health care, pharmaceuticals, nutraceuticals, and food processing (Sathasivam et al., 2019). Microalgae also aid as substitutes for fish oil, especially omega-3, Docosahexaenoic acid (DHA), Eicosapentaenoic acid (EPA), omega-6, and arachidonic acid (ARA) (Marella & Tiwari, 2020). A range of primary products that are possible from model pennate diatom *Phaeodactylum tricornutum* as reported in (Butler et al., 2020) are: EPA, DHA, ARA, Triacylglycerol (TAG), and Brassicosterol that forms the major components of lipids, and Chrysolaminarin forms the major portion of carbohydrates. Fucoxanthin, Lupeol, and betulin from the major terpenoids class in the model diatom *P. tricornutum*. A marine microalga, *Nannochloropsis oceanica*, is targeted as a source of EPA and violaxanthin. *Synechocystis* sp. and *Arthrospira* sp. belong to cyanobacteria used to extract phycocyanin, terpenoids, and polyhydroxy butyrate (PHB) (Mobin & Alam, 2017). Microalgae are valuable sources of vitamins like A, B1, E, C, B6, B12, riboflavin, nicotinic acid, biotin, folic acid, and pantothenate (Chittora et al., 2020).

### 2.2 Microalgae as Biofertilizers and Functional Foods

Ensuring food security to the burgeoning population in developing economies has been a significant challenge. Green practices are gaining attention with the adoption of eco-friendly technologies to sustain food production while reducing the risk of chemical-based fertilizers (Andrade, 2018). Cyanobacteria are emerging as low-cost and eco-friendly biofertilizers. They help control the nitrogen deficiency in plants and are known to improve water holding capacity, enhance aeration of the soil, and act as reservoirs of vitamin B12 (Hall et al., 1995). The efficient nitrogen-fixing bacteria are *Anabaena variabilis*, *Nostoc linkia*, *Calothrix* sp., *Tolypothrix* sp., *Spirulina platensis* (Chittora et al., 2020), which are useful as *N*, *P*, and *K* supplements for biofortification of soil (Anitha et al., 2016). Earlier studies show *Spirulina*, *Chlorella* sp., and *Palmaria palmata* helps in bio-augmentation $NO_3^-N$ and $NH_4^+N$ during its field application (Alobwede et al., 2019). Microalgae, primarily diatoms, are being used widely as feeds and high-quality nutritional supplements for bivalves, juvenile fishes and shrimp larvae, and post-larvae (Marella et al., 2020; Shah et al., 2018). Diatoms also produce vitamins and proteins beneficial for aquaculture growth with proven antibacterial and anti-viral properties against pathogens proliferating in aquaculture ponds. Table 1 lists the research institutions across the globe that are working on industrially relevant products from microalgae (diatoms) with details of targeted biomolecules.

### *2.3 Valorization of Secondary Products from Microalgal Biomass*

Cell walls of many microalgae are made of complex microfibrillar structures placed within a glutinous protein cell matrix (Yap et al., 2016). However, some microalgae that belong to Bacillariophyceae and Charophyceae family are protected by a rigid inorganic wall of silica or calcium carbonate (Bolton et al., 2016), and the growth environment significantly influences the thickness and microalgal cell wall composition (Praveenkumar et al., 2015). The cell wall is disrupted to extract lipid, which is done either by physical or chemical pretreatment methods to improve amenability of cell constituents by organic solvents. Various physicochemical cell disruption methods experimented with bead milling, osmotic shock, pulsed electric field, microwave, ultrasound, and freezing/thawing. Various pretreatment and bioenergy conversion processes used for bioenergy production from microalgal biomass are illustrated in Fig. 2.

Among diverse cell disruption methods, ultrasound treatment (sonication) is reported to improve the cell disruption efficiency of microalgae (Ramachandra et al., 2011, 2013). Microwave treatment was a rapid process that enabled 80% of the cell lysis (Abbassi et al., 2014). After cell disruption, either thermochemical or biological processes are carried out to derive secondary products like bioethanol, bio-oil, biogas, biobutanol, volatile fatty acids, biohydrogen, and biopolymers (Venkata Mohan et al., 2020). Gasification, pyrolysis, hydrogenation, liquefaction, and combustion are thermochemical conversion processes that involve applying heat energy to obtain end products. The energy obtained from such thermochemical processes is mainly gaseous forms or energy-rich biocrude that is upgraded to bioenergy products. Biological treatments such as anaerobic digestion, fermentation, and heterotrophic fermentation would result in biogas, bioethanol, alcohols, and liquid hydrocarbons, whereas physicochemical conversion using extraction and transesterification would lead to biodiesel (Jankowska et al., 2017). Possible bioenergy components from microalgal biomass from an energy perspective are methane, biodiesel, biocrude—possible refinement into gasoline and green diesel, biobutanol and ethanol, biohydrogen, and bioelectricity from microalgal carbohydrates. Figure 3 illustrates the valorization of microalgal biomass into various forms of bioenergy as secondary products.

**Table 1** Research institutions across the globe working on microalgae (diatom)

| Species | Research institution | Targeted biomolecules | References |
|---|---|---|---|
| *Navicula cincta, Nitzschia punctata, Amphiprora sp., Chaetoceros spp., Cyclotella sp.* | Indian Institute of Science, Bangalore | Biodiesel and EPA | Saranya and Ramachandra (2020) |
| *Amphora coffeaeformis* | Centre for advanced studies in botany, University of Madras, Chennai | Biofuel and essential fatty acids | Rajaram et al. (2018) |
| *Nitzschia paea, Gomphonema parvulum, Nitzschia inconspicua, Diadesmis confervaceae, Sellaphora sp., Placoneis elginensis* | Harish Singh Gour University, Madhya Pradesh | Diatom lipids and diatom solar panels | |
| *Pinnularia sp.* | School of Chemical, Biological and Environmental Engineering, Oregon State University, USA | Solar cells, batteries and electroluminescent devices, and diatom solar panels | Jeffryes et al. (2011) |
| *Coscinodiscus walesii* | National Council of Research Institute for Microelectronics and Microsystems-Department of Naples | Diatom solar panels | De Stefano et al. (2007) |
| *Synedra sp., Diatom consortium* | Noida International University, Uttar Pradesh | Fatty acids and triglycerides | Li et al. (2017) |
| *Achnanthes sp.* | Scripps Institution of Oceanography | Biofuel | Hildebrand et al. (2012) |
| *Halamphora coffeaformis, Navicula cincta* | Bahia Blanca, Argentina | Biodiesel and essential fatty acids | Martín et al. (2018) |
| *Diatom* | The University of Colorado, Boulder, USA | Diatom-based taxonomy and limnological studies | Andrejić et al. (2018) |
| *Diatom* | Rutgers University, New Brunswick, USA | Physiological and molecular aspects of diatoms | Kranzler et al. (2019) |

(continued)

**Table 1** (continued)

| Species | Research institution | Targeted biomolecules | References |
|---|---|---|---|
| *Phaeodatylum tricornutum* | Shandong University, China | Seasonal dynamics studies | Zhang et al. (2019) |
| *P. tricornutum, Skeletonema costatum* | University of Iceland, Reykjavik, Iceland | Anti-cancer compounds | Hussein and Abdullah (2020) |
| *Thalassiosira weisflogii, Cyclotella cryptica* | Istituto di Chimica Biomolecolare (ICB)—CNR, Via Campi Flegrei 34, 80,078 Pozzuoli, NA, Italy | Biofuel | D'Ippolito et al. (2015) |
| *Phaeodatylum tricornutum* | Swansea University, UK | Diatom biorefinery | Butler et al. (2020) |
| *Thalassiosira pseudonana* | University of Sheffield, UK | Bioactive compounds | Sethi et al. (2020) |
| *Thalassiosira weissflogi* | International Crop Research Institute for Semi-arid Tropics (ICRISAT), Patancheru 502 324, Telangana State, India | Diatom biorefinery | Marella and Tiwari (2020) |

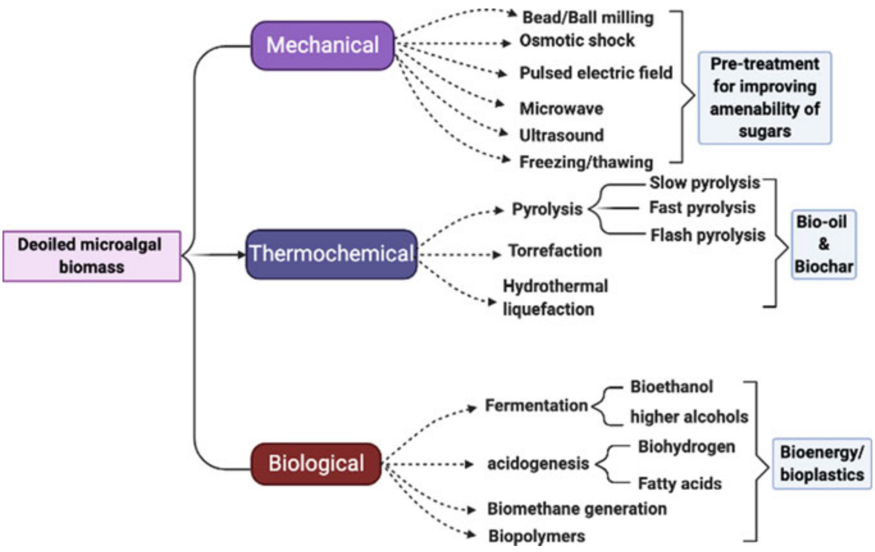


**Fig. 2** Different conversion processes for various energy products production from microalgae

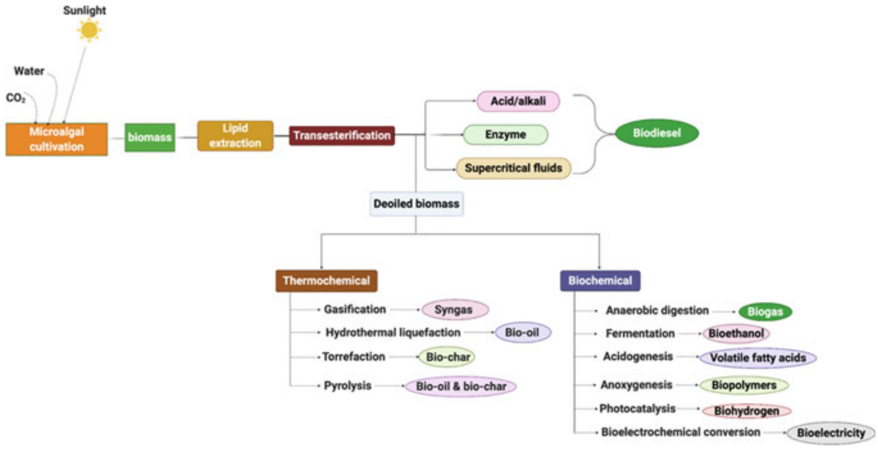


**Fig. 3** Valorization of microalgal biomass into an array of bioenergy (secondary) products

## 2.4 Biogas from Microalgal Biomass

Anaerobic digestion (AD) of microalgal biomass has emerged as a promising technology through the decomposition of organic matter by anaerobic bacteria into biogas. AD is a four-step process involving hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Ward et al., 2008). The main components of biogas are methane and carbon dioxide. The biogas quality is usually determined by the relative amount of methane, which depends on the substrate and operating conditions for anaerobic fermentation (Sialve et al., 2009). Several studies have shown the possibility of using spent. The microalgal biomass constitutes appropriate feedstock for biogas production as it contains a high quantity of proteins (51–64%), followed by carbohydrates (6–21%) and lipids (7–16%) (Jankowska et al., 2017) with a yield of 0.09–0.54 L $CH_4$ $g^{-1}$ (Sialve et al., 2009). However, the efficiency of biogas production is species-specific as complex recalcitrant cell wall structure and composition of some algae hinder the anaerobic digestion due to the inability to penetrate cell walls by bacteria (termed as anaerobic biodegradability). Hence, various pretreatment methods for disrupting cell walls include thermal, microwave, ultrasonic, chemical, and mechanical processes (Kwietniewska & Tys, 2014). A comparison of methane yields with and without pretreatment techniques is given in Table 2.

Techno-economic feasibility studies have demonstrated a 35% cost reduction in production (Harun et al., 2011), energy recovery, and improvement in the energy balance by integrating methane production with biodiesel production (Alzate et al., 2014; Francisco et al., 2010; Zhao et al., 2014). Energy recovery of 80% was recorded in a study that used *Isochrysis galbana* for integrated biodiesel and biogas production biorefinery approach.

**Table 2** Pretreatment methods and methane production from different microalgae

| Microalgae | Pretreatment | Operating conditions (Temp °C, days) | $CH_4$ production (mL $g^{-1}$ VS) | Reference |
|---|---|---|---|---|
| *Chlorella vulgaris* | Lipid extraction | 35, 25 | 314 ± 18 | Zhao et al. (2014) |
| *Nannochloropsis salina* | Without lipid extraction | 35, 25 | 557 ± 5 | Zhao et al. (2014) |
| *Phaeodactylum tricornutum* | Without lipid extraction | 35, 25 | 337 ± 15 | Zhao et al. (2014) |
| *Phaeodactylum tricornutum* | After lipid extraction | | 339 ± 13 | Zhao et al. (2014) |
| *Nannochloropsis gaditana* | Lipid extraction with ethanol | 35, 53 | 327 ± 2 | Alzate et al. (2014) |
| *Nannochloropsis gaditana* | Without lipid extraction | 35, 53 | 303 ± 5 | Alzate et al. (2014) |
| *Tetraselmis* sp. | Without lipid extraction | 38, 65 | 160 | Hernández et al. (2014) |
| *Tetraselmis* sp. | Supercritical $CO_2$ extraction | 38, 65 | 236 | Hernández et al. (2014) |
| *Scenedesmus* sp. | Without oil extraction | ND, 32–40 | 212.3 ± 5.6 | Ramos-Suárez and Carreras (2014) |
| *Isochrysis galbana* | After lipid extraction | 38, 30 | 310 | Sánchez-Bayo et al. (2020) |

*ND* data unavailable

## *2.5 Fermentation into Bioethanol*

Microalgae have been receiving attention as a carbohydrate feedstock for their effective fermentation into bioethanol. After lipid extraction, the deoiled biomass containing starch and cellulose can be used for bioethanol production (Shokrkar et al., 2018). Simultaneous saccharification and fermentation of microalgal biomass using enzymes have shown higher yields of reducing sugars with prospects in cost-effective fermentation into bioethanol (Shokrkar & Ebrahimi, 2018). A study on enzymatic hydrolysis of microalga *Chlorella vulgaris* as feedstock for bioethanol production resulted in a glucose yield of 90.4% (0.461 g/g biomass) bioethanol production (Ho et al., 2013). A microalgal biorefinery of microalga *Dunaliella tertiolecta* biomass after lipid extraction subjected to chemoenzymatic saccharification yielded 0.14 g/g residual biomass (Lee et al., 2013).

### 2.6 ABE Fermentation to Biobutanol

The microalgal residue with readily digestible polysaccharides like starch is being used as feedstocks for selective fermentation into higher alcohols such as biobutanol. For instance, green microalgae *C. vulgaris* is reported to accumulate starch in the range of 12–37% (Hirano et al., 1997; Spolaore et al., 2006). Microalgae can be cultivated throughout the year with a possibility of continuous harvesting (John et al., 2011), and less readily fermentable sugars such as galactose, xylose, and mannose are present only in minimal quantities, unlike lignocellulosic biomasses (Foley et al., 2011). Microalgae cultivation does not require arable lands and does not constitute a major food resource (Foley et al., 2011). Butanol has been sought after fuel in recent times owing to its superior alternative to ethanol considering (i) heating value, (ii) less volatile, and (iii) less corrosive, thus favourable for easy distribution and storage infrastructure. Biological production of biobutanol is achieved by acetone-butanol-ethanol (ABE) fermentation of microalgal biomass using a solventogenic anaerobic bacterium belonging to the genus *Clostridium.* This bacterium is known for its capability to convert a wide range of organic carbon sources, including glucose, cellobiose, arabinose, galactose, xylose, and mannose by secreting numerous polymer degrading enzymes such as alpha-amylase, beta-amylase and beta glucosidase, glucoamylase, amylopullulanase, and pullulanase (Ezeji et al., 2007a, 2007b). Incorporating these bacterial strains into carbohydrate-rich feedstocks under anaerobic conditions, the bacterium breaks down complex polysaccharides into butyric and acetic acid through an acidogenic process solventogenesis with the synthesis of acetone, ethanol, and butanol (Lee et al., 2008). Microalgal carbohydrates serve as feedstocks for fermentative bioethanol or biobutanol. Thus, the species-specific carbohydrate composition of microalgae determines the efficiency of ABE fermentation. The starch or carbohydrate contents of different microalgae are given in Table 3.

The carbohydrate content of microalgae varies significantly across species is divided into two functional components as (i) energy reserves (e.g., starch, glycogen) and (ii) structural polysaccharides (such as cellulose). The cell wall and storage components of cyanophycean members are lipopolysaccharides, peptidoglycan, and

**Table 3** Carbohydrate content of different microalgae

| Microalgae | Total carbohydrates (% dry weight) | Reference |
|---|---|---|
| *Nostoc* sp. | 52.3 | Efremenko et al. (2012) |
| *Dunalliella tertiolecta* | 50.6 | Efremenko et al. (2012) |
| *Arthrospira platensis* | 40.8 | Efremenko et al. (2012) |
| *Tetraselmis* sp. CS-362 | 26.0 | Brown et al. (1998) |
| *Nannochloropsis* sp. | 56.8 | Efremenko et al. (2012) |
| *Arthrospira platensis* | 40.8 | Efremenko et al. (2012) |
| *Scenedesmus obliquus* | 51.8 | Ho et al. (2012) |

**Table 4** Microalgae feedstock for biobutanol production

| Microalgae | Biomass treatment | Fermentative bacteria | Butanol production (g $L^{-1}$) | Reference |
|---|---|---|---|---|
| *Arthrospira platensis* | Sulfuric acid | *Clostridium acetobutylicum* B1787 | 9.13 | Efremenko et al. (2012) |
| *Nannochloropsis* sp. | Sulfuric acid | *C. acetobutylicum* B1787 | 10.9 | Efremenko et al. (2012) |
| *Chlorella vulgaris* JSC-6 | NaOH (1%), $H_2SO_4$ 3% | *C. acetobutylicum* ATCC 824 | 13.1 | Wang et al. (2016) |
| *Chlorella sorokiniana* (lipid extracted biomass) | $H_2SO_4$ (2%) + NaOH (2%) | *C. acetobutylicum* ATCC 824 | 3.86 | Cheng et al. (2015) |
| Wastewater algae | $H_2SO_4$ and enzyme treatment | *C. Saccharoperbutylacetonicum* N1-4 | 7.79 | Ellis et al. (2012) |

cyanophycean starch, respectively. Cellulose and hemicellulose are from the structural polysaccharides, while starch/lipids include the storage polysaccharides in species of Chlorophyta division. The cell wall component is absent in the division Euglenophyta, and the storage product comprises Paramylum/Lipid. Cellulose, agar, carrageenan, and calcium carbonate form the significant components of the cell wall, and Floridian starch is the primary storage component in Rhodophyta, owing to the variations in the cell wall, biological treatment of microalgae requires pretreatment methods based on cell wall compositions. The pretreatment methods aid in cell wall disruptions and make the internal storage components available for the microbial consortium. Different physical, mechanical, and thermo-chemical pretreatments have been experimented with to improve the bioavailability of microalgal cell components to increase fermentation efficiency for biobutanol production are given in Table 4.

Despite having numerous advantages, biobutanol production technology is still in its nascent stage, which warrants further investigations. The biorefinery approach of utilizing biofilm cultivated biomass after lipid extraction for ABE fermentation would have the potential of attaining economic feasibility with sustainable biofuel production.

## 2.7 Biocrude From HTL

Hydrothermal liquefaction (HTL) entails converting wet microalgal biomass into liquid biocrude by subjecting the biomass to a high temperature (280–370 °C) and pressure (10–25 MPa), circumventing higher energy costs in biomass drying.

Algal concentration ranging between 5 and 20%, HTL treatment can be carried out with just < 5% of the energy costs required for drying (Xu et al., 2011), and synthesized biocrude possess an energy value close to fossil petroleum (Jena & Das, 2011), which can be fractionated into different energy products. Hydrothermal degradation of microalgal biochemical constituents (carbohydrates, lipids, proteins) provides biocrude, a dark, viscous, energy-rich liquid (López Barreiro et al., 2013). Research on HTL has considerably increased, which is evident from publications related to HTL of *S. platensis*, *Botryococcus barunii*, *Desmodesmus* sp., *C. vulgaris*, and *Nannochloropsis* sp. (Biller & Ross, 2011; Brown et al., 2010). Typical elemental composition analysis of biocrude produced from Desmodesmus sp. with operating conditions of 375 °C for 5 min reaction time yielded 74.5% C, 8.6% H, 10.5% O, and 6.3% N with a higher heating value (HHV) of 35.4 MJ/kg. In comparison with other thermo-chemical conversion technologies of pyrolysis and gasification, HTL possess prominent characteristics such as (i) higher oil yield with the complete conversion of whole algal biomass into biocrude and other chemicals, (ii) elimination of drying process, (iii) higher lipid content (not an important criterion in HTL), (iv) enhanced HTL efficiency due to the enthalpy of phase change of water at higher pressure, (v) additional rectification or extraction is not required, and (vi) principal product is self-regulated (Tian et al., 2014). The current approach of biofuel conversion of algae to biodiesel needs to be economically viable. However, integration of HTL technology with current algae conversion technology would lead to sustainable utilization of algae residue after extracting lipids for biocrude production. Various experimental conditions of the microalgae-based HTL process, and its corresponding biocrude yields are given in Table 5.

**Table 5** HTL experimental conditions and biocrude yield reported on different microalgae

| Microalgae | Temp (°C), holding time (min) | Catalyst used | Biocrude yield (%) | Reference |
|---|---|---|---|---|
| *Botryococcus braunii* | 300, 60 | $Na_2CO_3$ (5%) | 64 | Dote et al. (1994) |
| *Desmodesmus* sp. | 375, 5 | No catalyst | 49 | Garcia Alba et al. (2012) |
| *Chlorella vulgaris* | 350, 60 | Pt/$Al_2O_3$ (1 mol $L^{-1}$) | 38.9 | Biller and Ross (2011) |
| *Nannochloropsis sp.* | 350, 60 | Pd/C | ~ 57 | Brown et al. (2010) |
| *Spirulina platensis* | 350, 60 | No catalyst | 39.9 | Jena and Das (2011) |
| *Nannochloropsis occulata* | 350, 60 | No catalyst | 34.3 | Biller and Ross (2011) |
| *Chlorella pyrenoidosa* | 280, 120 | No catalyst | 39.4 | Cheng et al. (2017) |

### 2.8 Algae as Feedstock for Biopolymers

Bio-based polymers are gaining significant attention over petroleum-based polymers due to their biodegradability and benign environmental characteristics (Garrison et al., 2016). A variety of bio-based raw materials such as resins and lignin derivatives, polysaccharides sourced from various feedstocks, proteins, and vegetable oils have been investigated for their suitability in bio-polymer production (Gandini, 2008). The current primary production of bioplastics is from terrestrial plant-based starch, and poly-lactic acid (PLA) polymers derived from corn and sugar beets (Sreedevi et al., 2014) competes with arable lands. Several bacterial strains capable of producing a range of exopolysaccharides and polyhydroxyalkanoates (PHA) have been commercially used as precursors for bioplastics (Rehm, 2010). However, with the enhanced plastic demand, and conventional plastics are posing significant threats to the environment, especially to marine ecosystems (Rahman & Miller, 2017). Microalgae secrete extracellular polymeric substances (EPS) comprising polysaccharides, proteins, lipids, and uronic and nucleic acids (Venkata Mohan et al., 2020). These EPS are being converted into bioplastics (polyhydroxyalkanoates (PHA), Polylactic acid (PLA), or thermoplastic starch (TPS) through the thermochemical conversion process by using glycerol as a co-substrate (Jerez et al., 2007). Biological routes of bioplastic production from microalgae are realized either through direct utilization and conversion of microalgal biomass or by utilizing the aqueous phase (hydrolysate) spent biomass as a source of nutrient for growing recombinant *Escherichia coli* which produces the bioplastic polyhydroxy butyrate (PHB) (Rahman et al., 2015).

### 2.9 Bioelectricity Through Microbial Fuel Cells

Microalgae-microbial fuel cells (mMFC) convert solar energy into electricity through a bioelectrochemical process through a combination of live and dead microalgae in respective cathodic and anodic chambers (Lee et al., 2015). In microbial fuel cell (MFC) technology, live microalgae are placed in a cathode chamber (photoreactor) that acts as a biocathode. This biocathode produces $O_2$ due to photosynthesis and acts as an electron acceptor from the external circuit (Wang et al., 2010). The anode chamber consisting of organics undergo digestion by releasing $CO_2$ and excess protons to the cathode chamber and also acts as an electron donor resulting in the generation of electricity (Juang et al., 2012). Live green algae growing in cathode chamber and used dead microalgal biomass as the substrate for anodic biofilm have been utilized to understand its feasibility for bioelectricity production. For example, microalga *C. vulgaris* grown in a cathodic chamber was found to photosynthesize increase the dissolved oxygen levels of the chamber. This increase in DO had a positive correlation with voltage output (Juang et al., 2012). The influence of light intensity on the cathodic resistance was investigated (Wu et al., 2014) and found that the light intensity was found to increase the rate of photosynthesis of *Desmodesmus* sp., resulting in higher $O_2$ levels, which enhanced the mMFC's cathodic resistance to induce bioelectricity. Though mMFC is at the nascent stages of research, substantial improvements have been made on microalgae coupled microbial fuel cell processes in recent years. However, further research is required to integrate this technology in a biorefinery approach to attain a circular bioeconomy.

## 2.10 Commercial Applications of Microalgal Biomass

Microalgae possess characteristics that are favourable for diverse commercial applications. The most important commercial application is in food nutrition as a protein source such as *Chlorella*, *Spirulina,* and *Dunaliella* (Javed et al., 2019). Studies have shown that microalgal biomass pellets have shown curing effects of gastrointestinal ailments through enhancement of intestinal Lactobacillus and treatment of renal failure (Yamaguchi, 1996). Green microalgae have potential applications in cosmetic industries, especially as sun and hair care products. For instance, *Chlorella* and *Arthrospira* sp. are being used as skincare essentials in the cosmetic industry as anti-irritants, anti-wrinkle agents, and anti-ageing creams. Algae like *Chlorella*, *Scenedesmus*, and *Spirulina* have been explored for their use as animal feed, especially as shrimp and aquaculture feed (Chuntapa et al., 2003). Microalgae are used as nutraceutical raw material for extraction of polyunsaturated fatty acid (PUFA), which is being used as an additive in infant milk and as feed to rear farm chicken enriches the amount of Omega-3 fatty acids in eggs (Pulz & Gross, 2004). Figure 4 illustrates the industrially relevant bioproducts possible from microalgae. Table 6 lists the price/ton for different microalgal species and estimated production per year.

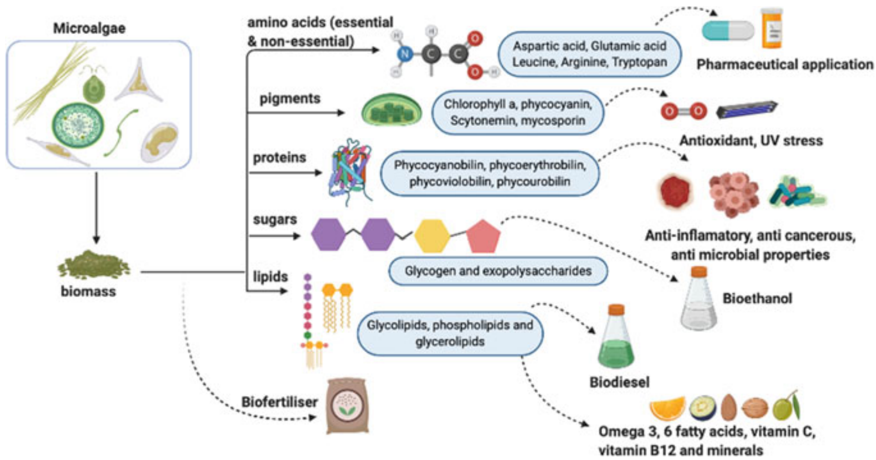


**Fig. 4** Different industrially relevant bioproducts extractable from microalgae

**Table 6** Estimated price per ton of microalgal biomass (Brennan & Owende, 2010; Tredici et al., 2016)

| Microalgae species | Estimated production in kilo tons per year | Price (millions)/ton INR |
|---|---|---|
| *Spirulina* | 3 | 2.99 |
| *Chlorella* | 2 | 2.99 |
| *Dunaliella* | 1.2 | 98.3 |
| *Crypthecodinium cohnii* | 0.24 | 3.5 (billion) |
| *Tetraselmis suceica* | 0.036 | |

## 3 Algal Refinery with Microalgal Bioreactor

The microalgal bioreactor was implemented using granite stones as substrates for microalgal cultivation in an abandoned *gazani* (flood plain where earlier salt tolerant paddy was cultivated) land present in the coastal regions of Karnataka. The various processes involved in the installation of the microalgal bioreactor are illustrated in Fig. 5.

The land preparation techniques required for setting up a microalgal bioreactor include: (i) liming, (ii) pitching, (iii) mud bank formation, and (iv) watergate installation. Land preparation is done using lime (in the form of crushed dolomite ($CaMg(CO_3)_2$) or crushed limestone ($CaCO_3$). Pitching is a process of levelling the land, which requires five persons working on the activity for 3-human days (7 h a day) in one-hectare land. A workforce of 2 persons for the 1-human day (7 h) is required for the liming activity. The granite stones are to be placed at an elevated position to avoid sediment interferences during microalgal biofilm formation. A combination of manual labour and machinery (JCB) is used for bioreactor installation.

Microalgae cultivated using substrate-based bioreactor has most diatoms in its species composition in the study region. Natural self-seeding of microalgae on the substrate was assumed with no addition of any external inoculum. A hybrid system involving harvesting manually and scrubbing using mechanized scrubbers at the end of a 5–7 days growth period was considered for the study. The drying of harvested algal biomass was carried out through direct solar drying in the first scenario while drying using a filter press, followed by solar drying in the second scenario. Transesterification of microalgal oil was carried out through direct transesterification of dried biomass using acid (dilute mineral acid (2% $H_2SO_4$) and biocatalyst (lipase). FAME conversion efficiencies of 83% for acid catalyst and 87% for biocatalyst was considered (based on conversion efficiencies obtained in prototype lab-scale experiments). Bioproducts from algal refineries include biodiesel, glycerol, biogas, algal meal, and fertilizer. Acid/biocatalyst-based transesterification of algal biomass results in biodiesel as the primary energy product and crude glycerol as the reaction byproduct. The crude glycerol after refining has diverse applications in the pharmaceutical and cosmetic industries. The spent algal biomass, when subjected to anaerobic digestion,

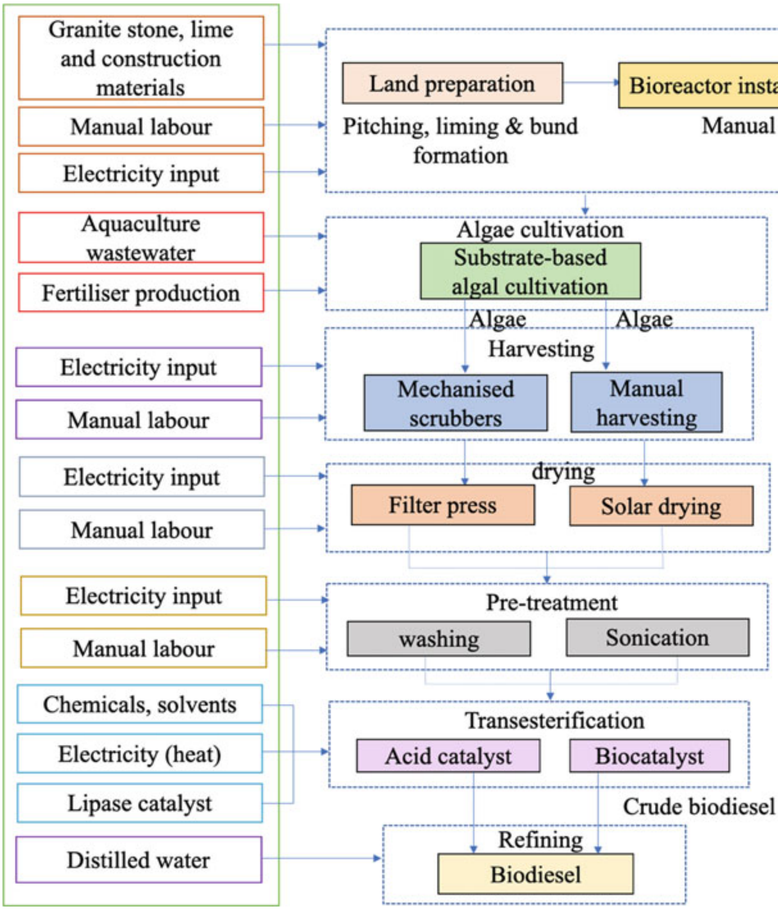


**Fig. 5** Processes in biodiesel production with material inputs

results in biogas. The solid residue left over after biogas production was considered a biofertilizer source with scope for direct application as a source of nitrogen in agricultural fields.

## *3.1 Techno-Economic Analysis*

Techno-economic analyses were carried out for a bioreactor in a one-hectare plot in the flood plains. Considering (i) different nutrients input, (ii) acid and biocatalysts (lipase), and (iii) varied FAME conversion efficiencies. Discounted cash flow model was used to assess the financial feasibility of the proposed microalgal cultivation system. The model considered 60% of the capital investments as project financing loans from the National Bank for Agriculture and Rural Development (NABARD) with an annual loan repayment determined by a 4.5% interest rate for a loan tenure of 5 years and the remaining 40% of farmer's investment share. The capital and operating (fixed and variable) costs were determined by considering the material and energy inputs at each stage (Table 7). The capital costs were estimated to evaluate the different processes considered with details of equipment, transportation costs, and raw material requirement incurred under each unit operation. Under capital costs, inventory of materials used for constructing bioreactor (granite stones for substrates, etc.) in a land area of 9000 m$^2$ (0.9 ha). The capital cost was fixed based on the actual market prices of the bioreactor materials and workforce requirements at the installation time. The cost of fermenters for biocatalyst production was included as an additional capital cost (in the biocatalyst scenario).

Operating costs include the following contributions: energy, materials, land lease, maintenance, and loan repayments. For operating cost estimation, the processes involved in algal biodiesel production were categorized into five different phases: (i) feedstock growth, (ii) biomass harvest, (iii) pretreatment, (iv) transesterification,

**Table 7** Methods used for techno-economic analysis

| Methods used for calculating techno-economic analysis | | |
|---|---|---|
| S. No. | Parameter | Calculation methods |
| Facility lifetime | | 30 years |
| *Capital cost* | | |
| 1.a | Bioreactor material/fermenter procurement | Actual prices from manufacturers |
| 1.b | Pitching, mud bank, and watergate installation cost | Through personal interviews and interaction with landowners and shrimp farmers |
| 1.c | Labour cost for land preparation | Fixed as per the minimum wages act after confirming the same with the current scenario in the study region |
| *Operating cost* | | |
| | Fixed operating cost | |
| 2.a | Gazani land lease value | Fixed as per current lease trend in the study region |
| 2.b | Labour cost for harvesting | Same as 1.c |
| 2.c | Loan repayment cost | Calculated by considering 4.5% interest rates on principal for a loan tenure of 5 years |
| *Variable costs* | | |
| 2.d | Cost of lime fertilizer and solvents | Actual prices of chemicals, fertilizers, and solvents |
| 2.e | Biodiesel production and other downstream processing costs | Fixed as per Karnataka electricity regulation commission's standard power tariffs for industrial uses |

and (v) refining biodiesel. The system boundaries were based on land preparation (pitching, liming, making mud banks, and watergate installation) until biodiesel refining. Both the energy expended and the material inputs were considered with associated costs for TE analysis. Under fixed operating cost, gazani land lease value ($C_{LV}$), loan repayment ($C_{LR}$), and workforce requirement for manual harvesting ($C_{ML}$) at the end of every cycle (considering 5–7 days cycling time) for a total of 32 cycles (excluding monsoon and initial colonization period). In variable costs, the costs of chemicals (lime, fertilizers) and solvents required on an annual basis to run the production facility were estimated, and the charges were fixed based on the market prices of the respective chemicals. The costs incurred due to the energy spent in each of the downstream processes were calculated by estimating the energy required to perform each unit operation and converting the energy into costs ($C_{EC}$) by multiplying the energy spent (kWh) with its standard power tariffs fixed as per the Karnataka electricity regulatory commission. Biodiesel production cost (INR/kg), payback period (years), return on investment, and annual profit (INR/ha/yr.) was calculated using Eqs. 1–4, respectively, assuming a facility lifespan of 30 years.

$$\text{Biodiesel cost} = \frac{\text{Total operating cost}(C_{TOC})(\text{INR})}{\text{Biodiesel production volume}(L)} \tag{1}$$

where

$$C_{TOC} = C_{FOC} + C_{VOC}; \quad C_{FOC} = C_{LV} + C_{LR} + C_{ML} \text{ and } C_{VOC} = C_{EC}$$

$$\text{Payback period} = 1 + n_y - \frac{n}{p} \tag{2}$$

where
$n_y$ = The year at which the last negative cumulative cash flow occurs
$n$ = The value of cash flow at the year $n_y$
$p$ = Cumulative value at first positive cash flow

$$\text{ROI}(\%) = \frac{\text{Total profit}}{\text{Total operating cost}} \times 100 \tag{3}$$

$$\text{Profit} = \text{Revenue} - \text{cost} \tag{4}$$

The detailed cost breakup on fixed capital investments and operating costs required for setting up a substrate-based microalgal cultivation setup is summarized in Tables 8 and 9, respectively. Capital investment for all three scenarios was the same (₹ 67,500 INR/ha) for bioreactor (substrate–granite stone: procurement and installation and ₹ 18,500 INR/ha for land preparation). Earlier studies considered land costs as a capital investment as land is purchased for setting up bioreactor facilities. For instance, a land cost of $7800/ha (Davis et al., 2011), $138,000/ha (Norsker et al., 2011), $1200/ha (Xin et al., 2016) was considered as capital cost. However, the land lease value (₹ 20,000/ha/yr.) of the abandoned flood plains was considered under operating costs in this study.

Other operating costs considered in the present study include manpower labour charges (₹ 28,800 INR/ha/yr.), transesterification (chemicals + energy) costs, and yearly loan repayment costs. The loan repayment cost was estimated as ₹ 22,368 INR/yr. for scenarios 1 and 2, considering 4% interest. In contrast, for scenario 3, the loan repayment cost was higher (₹ 50,040 INR/yr.), which was influenced by the fertilizer costs in the acid catalyst sub-scenario. In contrast, in the case of the biocatalyst sub-scenario, ₹ 67,116 INR/yr was estimated due to the additional costs required for fermenter procurement. The material input for acid and biocatalyst sub-scenarios was different among the three varying nutrient input scenarios as the nature and amount of chemicals, solvents, and reaction conditions were different for transesterification using acid and biocatalyst. The assumption on biodiesel yields achievable using acid and enzyme (bio) catalysts were also different (based on the FAME productivity). Thus, the significant scenarios (Scenario 1–3) were explained with two different sub-scenarios of acid and enzyme (lipase) as catalysts for transesterification.

The material and energy outputs considered for analysis were (i) algal biomass (AFDW) (kg/ha/yr), (ii) Biodiesel from the harvested biomass (kg/ha/yr), (iii) the quantity of crude glycerol obtained as a byproduct during the biodiesel process, and (iv) biogas production from spent biomass ($m^3$). Conventionally, biodiesel production produces 10% crude glycerol (v/v) as the main byproduct (Yang et al., 2012). Hence, 10% of the total biodiesel yield possible per ha area for a period of one year was taken as the crude glycerol yield. After lipid extraction, the biogas production potential of the spent algal residue was about 0.272 $m^3$ of biogas per kg of spent algal biomass used (Harun et al., 2011). Revenue estimation from microalgal cultivation setup includes byproducts from transesterification (crude glycerol) and other value-added products (biogas and spent biogas leachate as algal meal fertilizer) be generated out of the spent microalgal biomass rich in protein and polysaccharides. Estimates revealed that for assumed biomass productivity of 6.7, 15.3, and 28.8 tons/ha/yr under different nutrient input scenarios, acid catalyst-based transesterification could yield a biodiesel quantity of 1499.2, 3407.2, and 6388.6 kg (assuming 83% FAME conversion efficiency).

In contrast, for the biocatalyst scenario, a higher biodiesel yield of 1571.4, 3571.5, and 6696.6 kg is possible with an assumed 87% effective conversion of microalgal oil into FAME (biodiesel). FAME conversion efficiencies were based on the experimental results of using a different catalyst (Saranya & Ramachandra, 2020). To estimate the revenue possible from spent algal fertilizer, one-fourth of the spent microalgal biomass remained after biodiesel extraction and biogas production. Profit evaluation indicates that ~5 times more profit in scenario three than scenario one while using an acid catalyst and ~6 times more profit in biocatalyst scenario, which could be attributed to the higher FAME conversion efficiencies possible from biocatalyst. In addition, biocatalyst reduces the problem of environmental pollution otherwise posed by the acid catalyst. Return on investment is the percentage of initial investment that can be recovered annually as profit, and the payback period is the time required to retrieve investments. The return on investment (ROI) varied between 18.4

**Table 8** Detailed cost budgeting for different biomass productivity scenarios using acid catalyst

| Input costs | Different scenarios | | |
|---|---|---|---|
| | Scenario 1 | Scenario 2 | Scenario 3 |
| Fixed capital costs | Value (INR) | Value (INR) | Value (INR) |
| Gravel stones procurement | ₹ 67,500 | ₹ 67,500 | ₹ 67,500 |
| Pitching, mud bank formation, laterite stone purchase, liming, and water gate installation | ₹ 18,500 | ₹ 18,500 | ₹ 18,500 |
| *Operational costs* | | | |
| Gazani land lease value (per ha) | ₹ 20,000 | ₹ 20,000 | ₹ 20,000 |
| Fertilizer input cost (kg/ha/yr.) | – | – | ₹ 167,530 |
| Harvesting (manual) yearly manpower requirement (INR/yr.) | ₹ 28,800 | ₹ 28,800 | ₹ 28,800 |
| Biomass drying (shade drying) | NA | NA | NA |
| Transesterification (material + energy) costs | ₹ 9953 | ₹ 28,601 | ₹ 51,234 |
| Biodiesel purification cost | ₹ 1224 | ₹ 2734 | ₹ 5126 |
| Loan repayment | ₹ 22,368 | ₹ 22,368 | ₹ 50,040 |
| *Material and Energy Output* | | | |
| Biomass obtained per cycle (kg) | 211 | 480 | 900 |
| No. of cycles harvesting can be made (excluding monsoon) | 32 cycles | 32 cycles | 32 cycles |
| Biomass yield per year (kg/ha/yr.) | 6758.4 | 15,360 | 28,800 |
| Biodiesel production possible (kg) from harvested biomass | 1499.2 | 3407.2 | 6388.6 |
| Quantity of crude glycerol (byproduct) (L/ha/yr.) | 150.3 | 341.7 | 640.8 |
| Biogas production ($m^3$) | 1768 | 4019 | 7536 |
| *Revenue estimation* | | | |
| Revenue from biodiesel production (INR) | ₹ 89,863 | ₹ 204,233 | ₹ 382,937 |
| Revenue from crude glycerol | ₹ 3757.5 | ₹ 8543 | ₹ 16,020 |
| Revenue from biogas production using spent biomass | ₹ 16,230 | ₹ 36,896 | ₹ 69,180 |
| Revenue from spent algal residue as fertilizer (INR/ha/yr.) | ₹ 14,643 | ₹ 33,280 | ₹ 62,400 |
| Total revenue (INR/ha/yr.) | ₹ 124,493 | ₹ 282,951 | ₹ 530,537 |
| Payback period | 6.97 | 0.98 | 2.98 |
| Return on investment (%) | 25.0 | 95.7 | 50.8 |
| Biodiesel production cost (INR/kg of biodiesel) | ₹ 54.93 | ₹ 30.08 | ₹ 50.52 |
| Profit (INR/ha/yr.) | ₹ 42,148 | ₹ 180,449 | ₹ 207,807 |

**Table 9** Detailed cost budgeting for different biomass productivity scenarios using biocatalyst

| Input costs | Different scenarios | | |
|---|---|---|---|
| | Scenario 1 | Scenario 2 | Scenario 3 |
| Fixed capital costs | Value (INR) | Value (INR) | Value (INR) |
| Fermenter for biocatalyst production | ₹ 45,000 | ₹ 45,000 | ₹ 45,000 |
| Gravel stones procurement | ₹ 67,500 | ₹ 67,500 | ₹ 67,500 |
| Pitching, mud bank formation, laterite stone purchase, liming, and water gate installation | ₹ 18,500 | ₹ 18,500 | ₹ 18,500 |
| *Operational costs* | | | |
| Gazani land lease value (per ha) | ₹ 20,000 | ₹ 20,000 | ₹ 20,000 |
| Fertilizer input cost (kg/ha/yr.) | – | – | ₹ 167,530 |
| Harvesting (manual) yearly manpower requirement (INR/yr.) | ₹ 28,800 | ₹ 28,800 | ₹ 28,800 |
| Biomass drying (shade drying) | NA | NA | NA |
| Transesterification (material + energy) costs | ₹ 9953 | ₹ 28,601 | ₹ 51,234 |
| Biodiesel purification cost | ₹ 1224 | ₹ 2734 | ₹ 5126 |
| Loan repayment | ₹ 33,552 | ₹ 33,552 | ₹ 67,116 |
| *Material and energy output* | | | |
| Biomass obtained per cycle (kg) | 211 | 480 | 900 |
| No. of cycles harvesting can be made (excluding monsoon) | 32 cycles | 32 cycles | 32 cycles |
| Biomass yield per year (kg/ha/yr.) | 6758 | 15,360 | 28,800 |
| Biodiesel production possible (kg) from harvested biomass | 1571.4 | 3571.5 | 6696.6 |
| Quantity of crude glycerol (byproduct) (L/ha/yr.) | 150.3 | 341.7 | 640.8 |
| Biogas production ($m^3$) | 1768 | 4019 | 7536 |
| *Revenue estimation* | | | |
| Revenue from biodiesel production (INR) | ₹ 94,195 | ₹ 214,078 | ₹ 401,397 |
| Revenue from crude glycerol | ₹ 3757.5 | ₹ 8543 | ₹ 16,020 |
| Revenue from biogas production using spent biomass (INR) | ₹ 16,230 | ₹ 36,896 | ₹ 69,180 |
| Revenue from spent algal residue as fertilizer (INR) | ₹ 14,643 | ₹ 33,280 | ₹ 62,400 |
| Total revenue (INR/ha/yr.) | ₹ 128,825 | ₹ 292,797 | ₹ 548,996 |
| Payback period (years) | 17.67 | 1.27 | 2.96 |
| Return on investment (%) | 18.4 | 84.8 | 51.8 |
| Biodiesel production cost (INR/kg of biodiesel) | ₹ 59.52 | ₹ 31.83 | ₹ 50.74 |
| Profit (INR/ha/yr.) | ₹ 35,296 | ₹ 179,110.48 | ₹ 209,190 |

and 95.7% for the scenarios considered, with higher ROI (95.7%) was estimated for scenario 2 (wastewater input–acid catalyst), representing a possible favourable higher return on the investments made. The payback period for scenario 1 was the highest for biocatalyst (17 years) due to the projected less annual biomass productivity with estimated higher capital investment. However, the payback period for scenario 2 and scenario 3 was 1.27 and 2.96 years, respectively, showing the financial viability of the proposed algal reactor with biodiesel production. An earlier study that assessed the techno-economic viability of biodiesel biorefinery had demonstrated an ROI that varied between 18.21 and 23.12% and a payback period of 4.3–5.5 years for different process scenarios considered (Vlysidis et al., 2011). The most favourable and profitable among the three considered scenarios was found to be microalgae cultivation using aquaculture wastewater, especially because of its zero associated input value as a nutrient with the wastewater remediation benefits.

The unit production cost of biodiesel for scenarios 1–3 while using acid catalyst varied between ₹ 30.08 and 54.93 INR/kg of biodiesel. The cost of production for biocatalyst-based biodiesel production ranged between ₹ 31.83 and 59.52 INR/kg. The biodiesel production cost per kg of biodiesel for scenario 2 (wastewater input) was found to be the lowest (30.1–31.8 INR/kg biodiesel) while using both acid and biocatalyst of all the scenarios (Tables 8and 9), thus showing scope for optimal biomass productivity while incurring lesser material/energy costs with remediation benefits and lower GHG emissions and maximum profit. A mass balance of algal refinery byproducts of microalgal biomass was carried out by assuming a 100 kg dry algal biomass (Fig. 6). Considering a lipid content ranging between 18 and 26%, a biodiesel yield of 14.94–22.62 kg is possible when the biomass is subjected to direct transesterification. Crude glycerol of 1.49–2.26 kg is also produced as a byproduct during transesterification, which is estimated as 10% of the biodiesel (Rodrigues et al., 2017). The raw biogas obtained can be purified/upgraded by passing on to a $CO_2$ stripper absorption column or directly used for domestic cooking/heating applications. A 10% loss in biomass was assumed during the direct transesterification of microalgal biomass into biodiesel. The slurry left out after biogas production (~55–70 kg) can be used as an organic biofertilizer in agricultural fields.

Thus, a biorefinery-based microalgal bioreactor is proposed, which utilizes microalgal biomass to produce two different forms of bioenergy, such as biodiesel and biogas, in addition to the value-added products such as glycerol and biofertilizer. Deployment of such substrate-based microalgal bioreactor in the brackish water flood plains (that are left abandoned) along the coastal regions of Karnataka would provide a livelihood for the coastal population at a decentralized level through bioenergy production for their localized usage along with potential scope for GHG emission reduction through $CO_2$ sequestration.

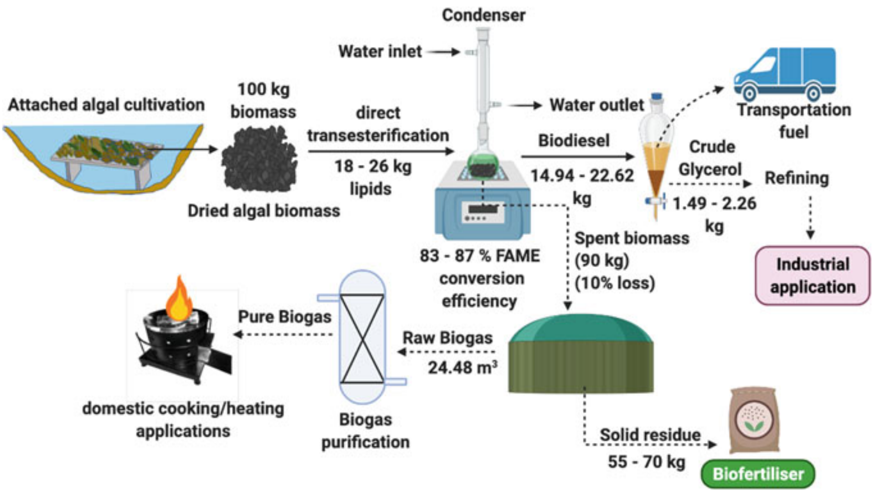


**Fig. 6** Schematics of mass balance of microalgal bioreactor from a biorefinery perspective

## *3.2 Circular Economy in Biorefinery*

One of the challenges in the advancement of the economic viability of microalgal biofuel is reducing the cost incurred in harvesting, drying, and lipid extraction processes. Biofilm-based algal cultivation helps in addressing the issues relating to harvesting, apart from addressing light limitation issues, while enhancing $CO_2$ mass transfer (Gross et al., 2015). Thus, integrating biofilm-based algal cultivation into a biorefinery would bring in multiple benefits (products) useful for diverse industrial applications apart from providing economic feasibility. As microalgae are rich in carbohydrates, they could be converted into a range of bioenergy components like biogas, biohydrogen, and liquid biofuels through different biological processes. Algal biomass, when subjected to anaerobic digestion, will result in biogas. The carbohydrates from algal biomass subjected to fermentation give butanol and ethanol. Acetone-Butanol-Ethanol (ABE) fermentation is an anaerobic fermentation process carried out using a gram-negative bacterium called *Clostridium beijerinckii*. Butanol is gaining considerable attention due to its superior fuel value and better storage characteristics. Another way of converting wet algal biomass produced is by hydrothermal liquefaction (HTL). HTL enables direct conversion of wet algal biomass into biocrude with medium temperature and pressure conditions varying between 350–550 °C and 20–25 MPa (Elliott et al., 2013). At specified operating conditions, the liquid water present in the algal biomass maintained at sub-critical levels act as a catalyst for biocrude production. HTL pathway to produce biocrude research is now in progress across the globe (Dote et al., 1994; Stephens et al., 2010; Wiley et al., 2013). This HTL process greatly reduces the energy spent on biomass harvesting and drying. Microalgal biomass rich in pigments like carotenoids is valuable as feedstock for bioactive/value-added product synthesis. The harvested

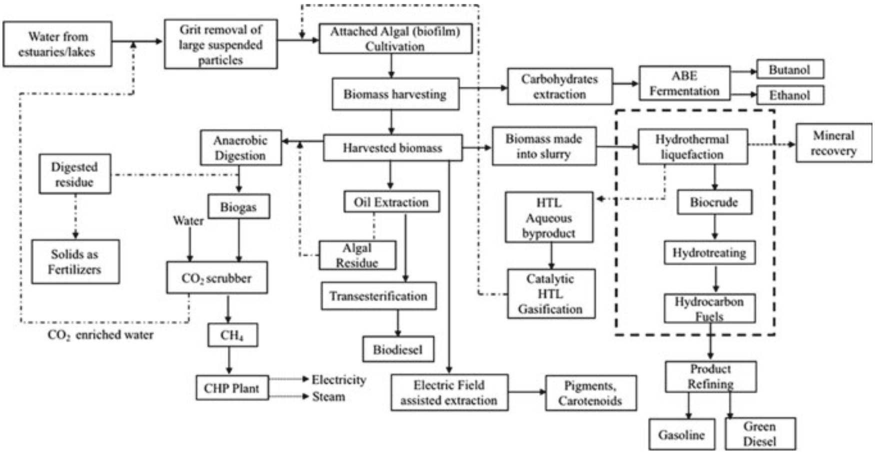


**Fig. 7** Sustainable biorefinery for utilizing microalgal biomass

biomass subjected to oil extraction and subsequent transesterification would result in biodiesel. A detailed illustration of various ways of utilizing algal biomass grown using a low-cost sustainable algal production system is shown in Fig. 7.

The current research focus is towards zero-waste biorefinery based on reducing, reuse, and recycling waste. Zero waste biorefineries eliminate the use of external energy or material inputs by understanding the material's use-value, efficient use of materials, and a planned framework on technologies for establishing a sustainable zero-waste biorefinery (Venkata Mohan et al., 2020). Microalgal cultivation in wastewater helps in the cost-effective treatment of wastewater with resource recovery. Thus, the biorefinery framework by using microalgae as feedstock provides a promising sustainable path with the circular bioeconomy.

## 4 Conclusion

Algal biofuel has emerged as a viable, sustainable solution to meet the growing demand for energy while addressing the environmental issues associated with the GHG footprint. Integrated bioprocessing through biorefinery approach by utilizing spent biomass after oil extraction can be used as a raw material for various energy products like bioethanol, methane, and biocrude and biofertilizers. The techno-economic analysis of microalgal biorefinery has demonstrated positive aspects such as (i) using appropriate substrates for microalgal attachment that considerably reduces the costs involved in harvesting; (ii) use of wastewater for optimal biomass production with reduced biodiesel production costs and less payback period; (iii) use of biocatalyst, though it increases the capital investment, environmental implications of mineral acids could be avoided which leads to significant environmental benefits. The utilization of microalgae grown using nutrient-rich wastewaters in an integrated biorefinery shows potential prospects in considerable energy and cost reduction. Establishing algal refineries at decentralized levels, especially along the Indian coasts, would empower local women of fisherfolk communities with secured livelihood opportunities with assured job opportunities.

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**Animal Ethics** The research does not involve either humans, animals, or tissues.

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# Biodiesel in Circular Economy

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## 1 Introduction

We currently live in a linear production system based on the economic model extract, manufacture, use, and dispose of, which is characterized by the production, management and consumption of resources, and goods and services in the short term. This has led to the depletion of a series of natural resources and fossil fuels, facing an imperative need for change. Faced with this model, the circular economy arises, closely related to sustainable development, since it is the point of concurrence of environmental, economic, and social aspects. This economic model is a sustainable system that focuses on the efficient use of resources, that is, on the continuous reuse of all elements in different stages.

The term circular economy was first proposed in 1989 by British environmental economists Pearce and Turner in the book "Economics of Natural Resources and the Environment". Subsequently, at the 2012 World Economic Forum 2012 in Davos, the Ellen MacArthur Foundation (EMF) and McKinsey Company published a report which evaluated the potential benefits of the transition to a circular economy (CE) as an opportunity of US $630 billion a year only for a subset of the EU manufacturing sectors and pointed out the significant environmental and social benefits derived from a circular economy (Ellen MacArthur Foundation, 2012). Ghosh (2020) affirmed that "a circular economy is a systems-level approach to economic development and a paradigm shift from the traditional concept of linear economy model of extract-produce-consume-dispose deplete to an elevated echelon of achieving zero waste by resource conservation."

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**Fig. 1** Circular economy cycle. *Source* Adapted (2020) portoprotocol.com

The circular economy is conceptually restorative and regenerative, promoting that raw materials, products, and services maintain their value and usefulness permanently, an aspect that must be considered from the design phase of these products and services until the end of their useful life cycle (Fig. 1).

This circular economy model, as opposed to the linear one, focuses on redesigning products, planning how to convert waste into raw materials, and innovating the product life cycle by changing the concept "from the cradle to the grave" to "cradle to cradle".

The circular economy is gaining impetus every day, some examples of which are as follows:

- Fibre from orange peel is used to make fabrics such as rayon and viscose for sustainable clothing (Sachidhanandham, 2020).
- Fats and used oil are used to produce biodiesel (Den Uil et al., 2003).
- Coffee waste is used to make textile fabrics, skin scrub, and garden fertilizer (Rathinavelu & Graziosi, 2005).
- Recycled PET can be used to make all kinds of garments and car mats and bottles (Majumdar et al., 2020).
- Old tires can be transformed into shoe soles (Shulman, 2019).
- Recycling grey or wastewater allows reuse for other purposes, such as toilet flushing or irrigation (Javadinejad et al., 2020).

# 2 Circular Economy in Bioenergy

Biofuels are a promising opportunity to achieve an innovative, low-emission circular economy while ensuring the protection of biodiversity and the environment, in addition to a new impetus for employment, growth, and investment. An example of this is biofuel production from spent oil, which is a waste product that has significant negative impacts on water, soil, and the health of the population. The circular approach starts by reinserting the spent oil into the production process as raw material to generate biodiesel. As a result of this process, by-products such as glycerin are also obtained, which can be sold as raw material for new manufacturing processes, creating products with cradle-to-cradle life cycles.

## *2.1 Biodiesel*

Biodiesel is a renewable fuel obtained from vegetable oils (VOs) and animal fats through a chemical reaction called transesterification, consuming short-chain alcohol, commonly methanol, in the presence of a catalyst. Chemically, biodiesel is a mixture of monoalkyl esters of long-chain fatty acids, most commonly methyl esters, so it is also known as fatty acid methyl ester or FAME. Nowadays is the second most-produced biofuel in the world, only behind bioethanol.

According to Knothe (2010), it is recognized that Wang first proposed the term biodiesel in his paper from 1988 entitled "Development of biodiesel fuel". However, the use of alkyl esters derived from vegetable oils as fuel was first reported by Chavane in 1937, in the Belgian Patent 422,877 "Procedure for the transformation of vegetable oils for their use as fuels". The first report on the use of what now is called biodiesel dated from 1942, when palm oil ethyl ester was used to fuel a bus travelling approximately 30 km from Brussels to Louvain in Belgium in 1938.

Prior to the 1990s decade, it is possible to found reports on the performance of both VOs or esters of vegetable oils as diesel fuels in power diesel engines (Freedman & Bagby, 1989; Goering et al., 1982; Lazarus & Pitt, 1984; Pryde, 1983; Pryor et al., 1983). This tendency is directly related to the petroleum crises of the 1970s, which was a significant breakpoint for the international interest in biofuels, mainly in non-oil producing countries. As an example of this renewed interest, it can be cited the National Alcohol Program (proálcool) in Brazil, through which the agro energy model was piloted and showed to the world for the first time (Stolf & de Oliveira, 2020). Subsequent oil prices and economic crises have triggered the impulse to bioenergy projects worldwide, notably in the USA and Brazil, which have been the major producers of biodiesel and bioethanol in the world for more than two decades (British Petroleum, 2020).

## 2.2 Use and Consumption

As previously mentioned, biodiesel was developed as a partial substitute or drop-in fuel for engines consuming diesel fuel, also named gasoil or light fuel oil. Transesterification of triglycerides from vegetable oil (VO) or animal fat produces monoalkyl esters with some physical properties that are more similar to diesel fuel than straight VO. Table 1 shows some selected parameters of biodiesel according to technical standards and compares them with those of petroleum diesel, soy, and rapeseed oils. Biodiesel is closer to diesel fuel regarding viscosity and density. However, flash point values and distillation temperatures are quite different, these being related to the volatility of the fuel and thus improving safe handling and toxicity to humans.

Consequently, biodiesel is used as a partial substitute of diesel fuel in all its applications or consumer sectors, from the road, rail, and waterborne transport, also in thermal machinery at industry and power generation. Specific substitution percentage or blending proportion of biodiesel with petroleum diesel depends on the type of machinery. In general, for diesel motor vehicles, an interval of 6–20% volume is accepted, according to ASTM 7467 standard. For more heavy machinery such as tractors or even external combustion equipment such as industrial boilers, a higher blending percentage has been reported (Ghorbani et al., 2011; Li et al., 2006; Macor & Pavanello, 2009; Simikic et al., 2018).

Since biodiesel is a partial substitute for petroleum diesel, its market is directly related to the diesel market. Worldwide, diesel fuel has reached a first place as the main petroleum-derived fuel consumed in the world, according to BP Statistical Review of World Energy (2020), with global consumption of 27.9 million barrels per day, against 24.3 million of gasoline. It is Asia–Pacific region the main consuming region in the world (~34%), followed by Europe (~24%) and North America (~18%). Detailed analysis shows that the USA is the bigger consumer of diesel (4 MMbbl), followed by China (3.69 MMbbl), India (1.72), and Germany (1.11). Figure 2 shows the consumption of petroleum-derived fuels for 2019.

Consumption analysis by the final sector clearly indicates a clear niche for biodiesel in the transport sector. IRENA roadmap (IRENA, 2019) identifies a growth of ~400% for biofuels contribution to 2050 horizon. In the specific case of biodiesel,

**Table 1** Comparative of selected physicochemical properties for petroleum diesel, biodiesel, soybean, and rapeseed oils

| | Petroleum diesel | Biodiesel | Soybean oil | Rapeseed oil |
|---|---|---|---|---|
| Viscosity ($mm^2/s$) at 40 °C | 2.71[a] | 4.21[d] | 33.1[b] | 35.5[c] |
| Density ($g/cm^3$) at 15 °C | 0.837[a] | 0.88[d] | 0.914[b] | 0.920[c] |
| Flash point (°C) | 55[a] | >130[d] | 274.8[b] | 257.9[b] |
| Distillation temperature (°C), 90% | 350[a] | 360[d] | – | – |
| Net calorific value (MJ/kg) | 42.6[c] | 39.9[d] | 39.6[b] | 37.06[c] |

[a]Alptekin and Canakci (2008); [b]Kralova and Sjöblom (2010); [c]Emberger et al. (2016); [d]LaNDACBio (2020)

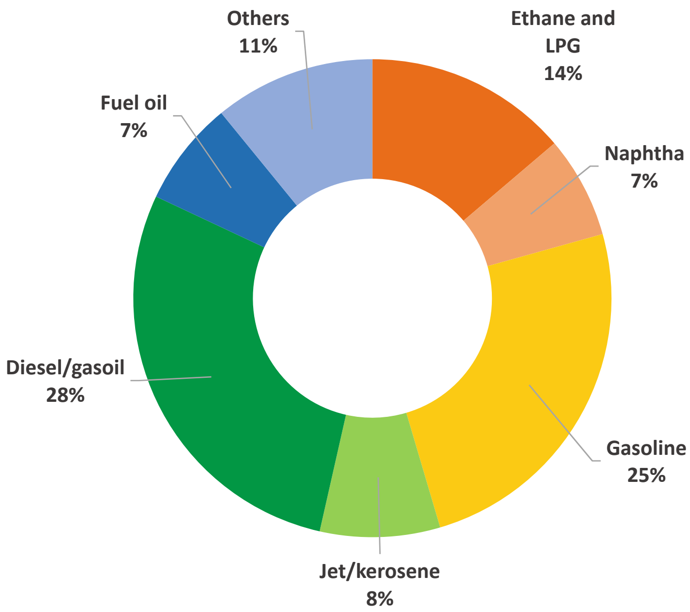


**Fig. 2** World consumption of petroleum-derived fuels in 2019. *Source* British Petroleum Statistical Review of World Energy (2020)

the forecast indicates expected growth of ~400%, from 35 to 180 billion litres per year from 2016 to 2050.

## *2.3 Feedstocks*

As mentioned before, biodiesel origin was closely related to the necessity to transform VO to decrease both density and viscosity and thus improve its performance in diesel engines and machinery. Both VOs and animal fats are triglycerides or triacylglycerols, consisting of a glycerol backbone with three fatty acids, and are organic compounds or relatively high molecular weight. Hence, biodiesel is defined as a transesterification product by the reaction of VO or animal fat with alcohol, mainly methanol, in the presence of a catalyst, preferably a miscible base such as sodium or potassium hydroxide.

Since homogeneous basic catalyzed transesterification is the predominant route to obtain biodiesel at an industrial scale, high-quality feedstocks as refined VOs constitute the main source of triglycerides. Oil crop selection varies depending on the geographical region, mainly due to agroclimatic conditions and agriculture policies. Soybean predominates in America, while rapeseed is the main crop of oil in Europe and palm in Asia (USDA, 2021).

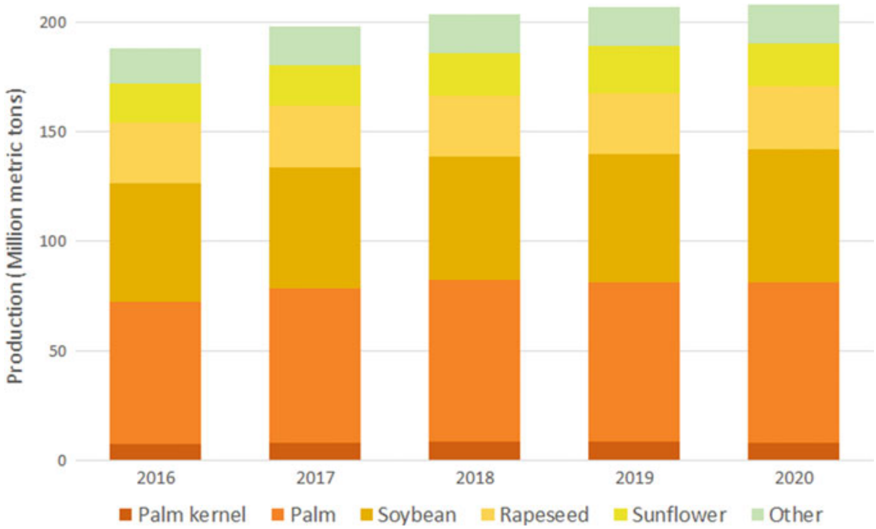


**Fig. 3** Global production of vegetable oil in 2015–2020. *Source* USDA (2021)

Thus, biodiesel feedstocks are inherently related to the oilseed world market and industry. Global production of VO has grown steadily for the last twenty years; the main crops worldwide are palm, soybean, and rapeseed, which are at the same time the main feedstock for biodiesel production at this time. Figure 3 shows VO world production in 2016–2020, in which palm was the main VO produced throughout all this period.

Main VO producers are Indonesia (49.4 MMton), China (28.83 MMton), Malaysia (20.21), European Union countries (17.87) and The United States (12.96), as shown in Fig. 4.

## *2.4 World Producers*

The biodiesel industry was born in Europe in the late 1990s, and by the year 2000, six countries of this continent, France, Germany, Italy, Spain, Czech Republic, and Austria, reported biodiesel production of 15.78 Mbbld. Their production was based mainly on rapeseed oil (FAO, 2008). Ten years later, in 2010, the main producers were Germany, Brazil, France, Argentina, and the USA, whose production represented 55% of the global amount of 356.55 Mbbld, being rapeseed in Europe and soybean in North and South America the main oil crops feeding biodiesel industry during those years (British Petroleum, 2020).

Recently, in 2019, biodiesel world producing map changed considerably. The main five producers are Indonesia, the USA, Brazil, Germany, and Argentina, for

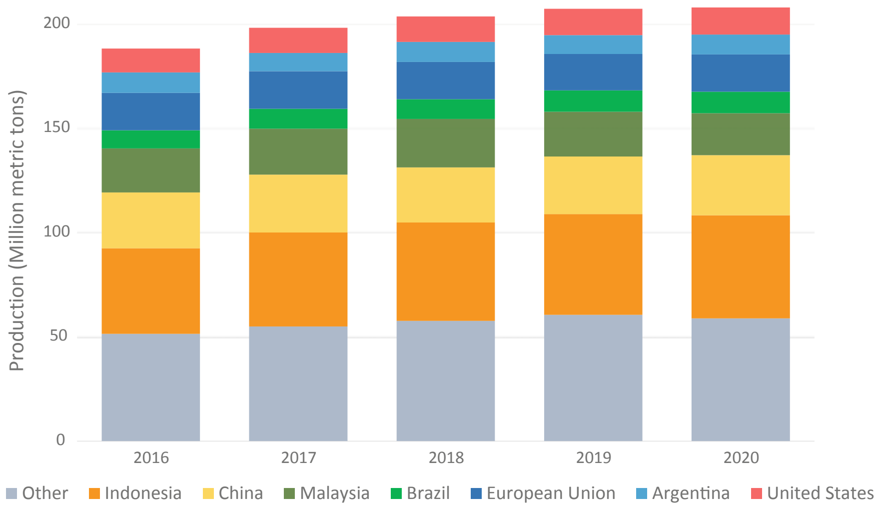


**Fig. 4** Vegetable oil production by country 2016–2020. *Source* USDA (2021)

a global production of 785.74 Mbbld, of which these five countries represent 58%. Asia–Pacific Countries base their production on palm oil (REN21, 2020).

## *2.5 Biodiesel Costs*

At present, the biodiesel production cost is highly dependent on VO price, reaching in some cases an 80% of production cost (Atabani, 2013; Iowa State, 2019). Other significant contributors are alcohol, catalyst, and labour costs. Even in the case of WCO to biodiesel schemes, oil cost could represent 60–70% of production costs (Mohammadshirazi et al., 2014). In the USA, biodiesel prices are strongly linked to soybean prices, around 2.8 and 3.5 USD/gallon, equivalent to 70–87 EUR/MWh (Brown et al., 2020; Iowa State, 2019). Figure 5 shows the cost breakdown for average soybean oil-based biodiesel in the USA.

National policy in the USA has promoted the production and consumption of biodiesel produced from local crops such as soybean and sunflower, and in some states such as California, a specific rule applies to promote low carbon intensity biodiesel (Fingerman et al., 2018). Under such a robust framework, biodiesel and biodiesel blend prices are competitive with petroleum diesel, and market penetration is viable.

Nevertheless, in most countries, even those dedicated to producing biofuel, this is not the case, so continuous effort is placed to diminish feedstock prices or discover alternative feedstock, preferably nonedible at a low price to increase the cost competitiveness of biodiesel and decrease environmental impacts.

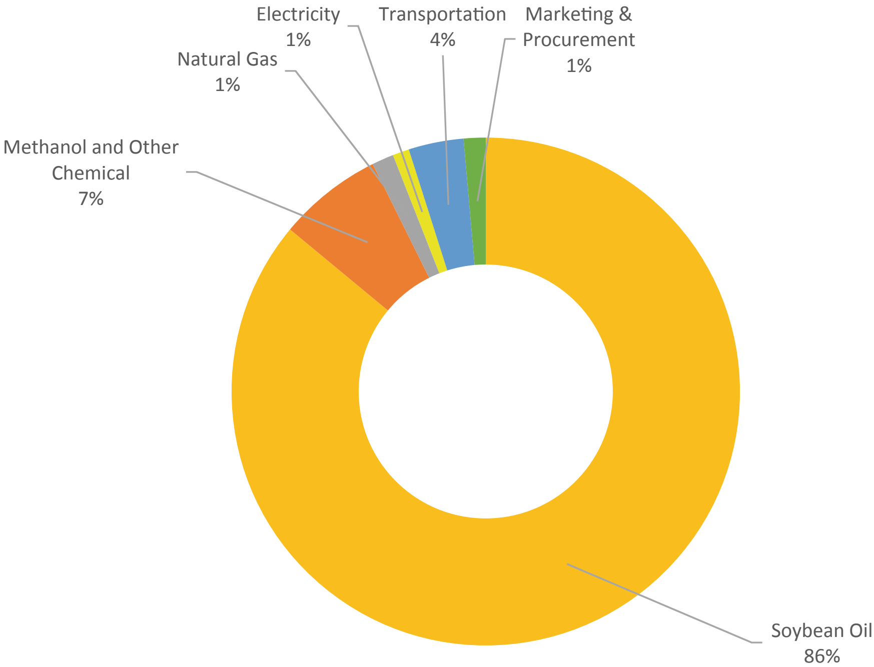


**Fig. 5** Cost breakdown for biodiesel production. *Source* Authors with data from Iowa State University and C. o. A. D. (2019)

## 3 Linear Economy of Vegetable Oil

Previous reports calculated a potential global waste cooking oil (WCO) generation of approximately 15 million tons per year (Gui et al., 2008). There is a reasonable uncertainty associated with these quantities since the real amount of WCO collected is a function of food preparation processes, nutrition habits, regulation of waste disposal, economic incentives, etc. Additional sources of relatively high quality are lipid fractions from industry, such as distillers corn oil in the USA or animal fat waste in general (Noureddini et al., 2009; Toldrá-Reig et al., 2020; Veljković et al., 2018).

In the specific case of WCO, once VO is used for food preparation or cooking, a considerable amount of it is discarded through sewer house lines, diverse water bodies or soils, causing pollution issues as well as obstructing the drainage systems and promoting the spread of plagues (Keener et al., 2008; Williams et al., 2012). Another issue related to WCO in the usual business model is recycling these oils for food preparation in the streets or animal feed. This oil is of lower quality and can contain several contaminants and toxic substances towards human health (Zhang et al., 2013; Zhao et al., 2015). Thus, correct recycling of WCO to obtain a renewable fuel of low carbon intensity is a better alternative.

Previous studies around the world can serve to calculate WCO generation potential. Radich reported that the total recovery of WCO in 1998 in the USA, confirmed by field recollection, was 1.25 million metric tons per year. If one correlates the national VO production for the USA in that year, which was 9.43 million tons, then an estimate of WCO gross recovery factor can be calculated as 0.13. Extrapolating these figures to the current time considering a global production of VO of 208 million metric tons, global WCO gross generation would ascend to 20.8 million metric tons. Alternatively, this figure could be contrasted to other calculation methodologies previously reported. One of particular interest is based on the consumption of refined VO to which some recovery factors could be applied; Eq. 1 shows the calculation rule according to Sheinbaum-Pardo et al. (2013).

$$\mathrm{WCO_a} = \mathrm{VO_c} * R_\mathrm{r} * R_\mathrm{c} \quad (1)$$

where

$\mathrm{WCO_a}$ is the waste cooking oil available

$R_\mathrm{r}$ is the recovery ratio of WCO to fresh oil consumption

$R_\mathrm{c}$ is the percentage of WCO most available for collection (equal to % of the population in urban areas).

Some authors (Giraçol et al., 2011; Sheinbaum-Pardo et al., 2013) suggest the use of recovery factors of 0.25–0.45, from which a world WCO production as a subproduct of the food industry and domestic use would ascend to 41.6–93.6 million metric tons. Then, as Sheinbaum et al. suggest, a second recovery factor can be used to represent the fraction of WCO that can be collected, using the fraction of the local population living in urban or metropolitan areas (Sheinbaum et al., 2015). Thus, by considering recent data from the World Bank, on the average percentage of the urban population in the world of 55%, and applying this to the WCO produced globally, one obtains 22.88–51.48 million metric tons of WCO available from the collection in urban areas around the world.

By applying this calculation methodology to main VO consumers, with $R_\mathrm{g}$ of 0.2, data from Table 2 can be obtained.

A review of WCO production and potential recollection reveals a vast potential for recycling this waste or by-product from the food sector towards a low carbon intensity model. For the past ten years (2010–20), the VO production (and therefore the WCO generated) has grown in 40–53% around the world, reflecting the increase in per capita consumption of refined VO in several countries, among which is worth to mention the USA, EU countries, and China.

The case of non-producing seed oil countries that simultaneously appear within the 15 top oil-consuming, such as Mexico, is particularly interesting. These could find a sustainable and rapid route to benefit from this waste to decarbonize high strategic carbon-emitting sectors such as energetic, without the necessity to increase the exploitation of natural resources.

**Table 2** WCO produced and available from main VO consumers in the world and Mexico in 2020

| Country | Vegetal oil consumption (MMton/year) | WCO produced as by-product (MMton/year) | Urban population[a] (%) | WCO available from recollection (MMton/year) | WCO *per capita* generation (kg)[b] |
|---|---|---|---|---|---|
| China | 39.82 | 7.96 | 61 | 4.86 | 3.47 |
| European Union | 25.79 | 5.16 | 75 | 3.87 | 8.65 |
| India | 22.20 | 4.44 | 35 | 1.55 | 1.12 |
| Indonesia | 18.01 | 3.60 | 57 | 2.05 | 7.49 |
| USA | 16.00 | 3.20 | 83 | 2.66 | 8.07 |
| Brazil | 9.67 | 1.93 | 87 | 1.68 | 7.90 |
| Mexico | 2.96 | 0.59 | 81 | 0.48 | 3.72 |

[a]United Nations Department of Economic and Social Affairs Population Division (2019); [b]World Bank, consulted online: https://data.worldbank.org/indicator/SP.POP.TOTL

## 4 Specific Generation Sectors

Global availability of WCO and its detail by country and per capita contributions are general calculations to identify gross WCO potential. The next level of detail is required to identify specific sources of WCO by locality and economic activity. For example, per capita, WCO generation does not imply that one inhabitant is going to generate that amount at home, but is the average contribution of that person due to its consumption in restaurants, hotel facilities, industrialized food, etc. Figure 6 shows WCO generation by an urban source, according to Singh et al. (2021).

Only those countries that have implemented systems for WCO recycling have enough and robust information systems to trace generation sources at the local level, from which more exact WCO generation figures could be obtained. Unfortunately, this is the exception and not the rule around the world, and paradoxically unless recycling programs of fats and waste oils are implemented, the real potential of WCO could not be determined, and gross estimation based on general quantities of local consumption and gross recovery factors is the only available figures at the beginning of production programs. Thus, only those countries or localities with mature environmental policies and sufficient budget can act on the WCO issue and turn it into an opportunity to implement a circular economy model.

## 5 Circular Economy of Waste Vegetable Oil Towards Biodiesel Production

Biodiesel produced from WCO is a low carbon and low impact energy alternative for urban environments in developing countries. Global potential production of WCO

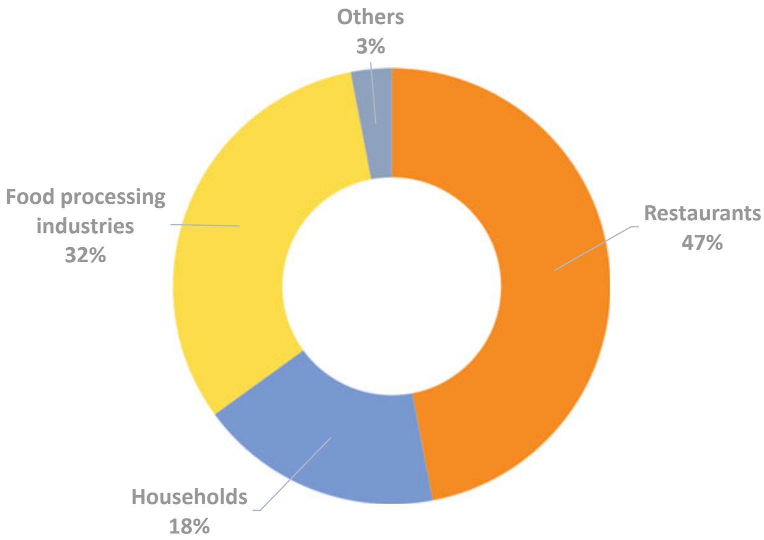


**Fig. 6** Sources of WCO generation. *Source* Singh et al. (2021)

has been addressed in the previous section and the particular interest case of non-producing seed oil countries such as Mexico, which simultaneously show a relatively high per capita consumption of this VO.

In addition to WCO generation potential, other factors must be considered to implement a circular economy model for WCO recycling, such as identification of the valuable product to be obtained from waste and market capacity to absorb the alternative or substitute, in this case, biodiesel from WCO. Three aspects should be addressed towards a more detailed analysis, i.e. (i) alternative valorization routes for WCO, (ii) barriers or opportunities to capitalize the WCO recollection potential, and (iii) energy and environmental policies required to reach the theoretical scenarios of maximal ecoefficiency. These factors can vary notably depending on the country or even between regions or localities. However, the international experience has shown that they are even as important as the amount of WCO generated to set up a successful circular economy model.

## 6 Barriers for WCO Collection

Barriers to WCO collection are related to the high dispersion of generation sources in urban areas, lack of regulation and economic incentives, and environmental education usually correlated to income level. The complexity involved in WCO collection augments as fragmentation of sources does. The industrial sector of fried food elaboration could be considered a stationary source since it can produce at a single facility a relatively high amount of WCO, and therefore, the collection from these sources would be the easiest (~30%) and the most profitable for recycling companies. On the next level, there are the generators from the services sector such as restaurants and hotels (~50%) or area sources. These ate more disperse than industry but less disperse than domestic generators. Finally, the household sources represent ~20% of WCO generation, being the most complicated sector to implement collection of WCO.

## 7 Alternative Valorization Routes

Assessment and implementation of valorization alternatives are complex issues influenced by techno-economic, environmental, and regulatory aspects. Transformation processes performed on a waste feedstock such as WCO depend upon a balance between feedstock properties and the required quality for recycled products. WCO is a mixture of VO wastes, and its lipid profile depends on the VO consumption profile of a locality. Thus, the most probable scenario in the Asia–Pacific region is that palm oil predominates in WCO fatty acid profile, whereas America is more likely that soybean oil does. Also, as WCO is a mixture of triglycerides, which are carboxylic acid derivatives, they can suffer from hydrolysis reactions in the presence of water (humidity) and heat. This reaction releases free fatty acids (FFA) and produces monoglycerides, diglycerides, and other oxidation products that could be toxic for human consumption or direct use. The FFA content in VO or animal fat is a known measure of its quality. In transesterification reaction via base catalysis, FFAs react with the base, producing carboxylates, commonly named soaps, which are undesirable compounds in finished biodiesel. Table 3 shows some relevant physicochemical properties of WCO, which quality and, therefore, price, is mainly determined by FFA and water content.

Designing a cost-effective valorization route means that maximum economic value would be obtained from a low investment-high value combination, depending

**Table 3** Physicochemical properties of WCO

| Property | Value |
|---|---|
| Water content (%wt) | 0.1–2[a,b] |
| Density (kg $m^{-3}$) | 0.9–0.92[c] |
| Kinematic viscosity (°C) @40 °C | 40–45[d] |
| Saponification value (mg KOH/g) | 190–207[a] |
| Acid value (mg KOH/g) | 2–4[a–c,d] |
| Iodine number (g $I_2$/100 g) | 80–127[a,b,e] |
| Higher heating value | 36–39[b] |

[a]Wen et al. (2010); [b]Sanli et al. (2011); [c]Degfie et al. (2019); [d]Contreras-Andrade et al. (2014); [e]Jalkh et al. (2018)

upon more complex aspects such as market penetration and local regulation. Nevertheless, designing a sustainable valorization route also means that environmental and health effects are considered, hence the importance to develop an adequate legal framework to support circular economy initiatives. Specific matrix varies among regions and localities, but it is particularly complex in countries with developing economies. From a technical point of view, low energy and material intensity routes would be more efficient. However, market aspects should also be considered. Previous reports enlist some valorization alternatives or secondary markets for WCO, among which soap obtaining, livestock meal formulation, and biodiesel production are already an economic reality. Some other options are plastic additive and polymerization additives (Feng et al., 2018; Kamilah et al., 2013; Liu et al., 2021). Figure 7 shows three valorization routes or secondary markets for WCO.

Soap obtaining has been reported to be a practical route for the valorization of WCO (Legesse, 2020; Li et al., 2020; Tsai, 2019); general processing is relatively easy and basically consists of infiltrating the oil to remove solids and the bleach with hydrogen peroxide it to eliminate impurities (Antonic et al., 2021; Maotsela et al., 2019) and unpleasant odorous substances. Further steps are chemical reaction with an alkali to form a carboxylate or soap, and final formulation with fine chemicals is required to reach the market as a higher added-value product. However, due to the potential degradation of physicochemical properties of WCO, the use for human consumption may be restricted owing to the presence of aldehydes and other oxidation products that may not be fully eliminated (Cai et al., 2015; Maotsela et al., 2019). In addition, although the obtained product a priori presents lower carbon intensity than soap obtained from fresh, natural resources, its use does not represent an advantage to diminish the GHG emissions in a critical emitting sector such as energy supply. From an economic point of view, and considering that process has

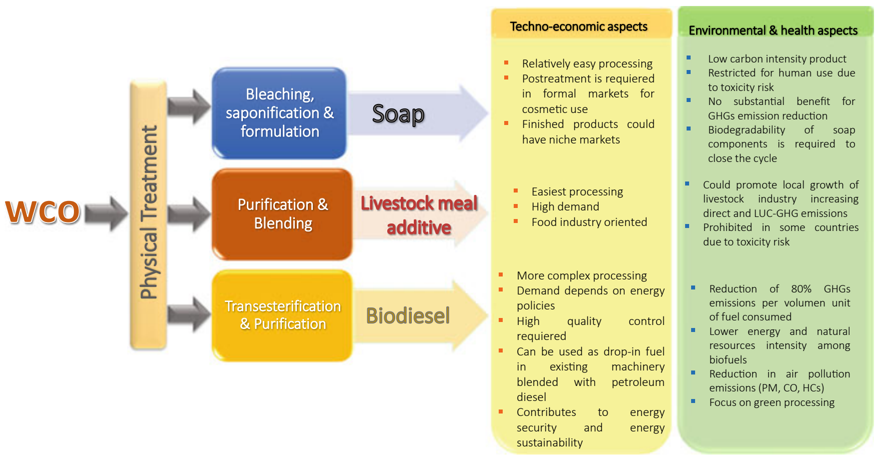


**Fig. 7** Analysis of three main valorization routes of WCO, gross analysis of benefits, and costs from the technical–economic and environmental perspectives

the fully covered quality and toxicity requirements for human use, its introduction to the market represents high variability depending on the market niche to be exploited, which in turn depends on income level, marketing, etc.

The use of WCO to produce livestock meals is a common practice (Panadare, 2015). Traditionally, the use of fresh VO for animal consumption represents nutritional benefits as they serve as a source of essential amino acids, high caloric content, etc. However, the composition of WCO differs from that of VO due to thermochemical degradation during its use in food preparation. There are some reports about the occurrence of toxic substances such as dioxins and lipid peroxidation products as aldehydes or ketones generically named 2-thiobarbituric acid reactive substances (TBARSs) (Erickson, 1997; Wei, 2011). Due to this problem, some countries have established regulations to ban the use of WCO for animal feeding or only permit the operation of certified suppliers, which must demonstrate that they fulfil quality standards. Significant are Regulations (EC) No. 1774/2002 and (EC) No. 1069/2009 of the European Parliament in the form of the Animal By-Products Regulations banning the use of WCO for animal feed. Unfortunately, these regulations are the exception and not the rule in other world regions, particularly in developing countries where the livestock industry is an important sector of the traditional economy.

Biodiesel production from WCO has been extensively described both in academic papers and commercial production reports and nowadays is a commercial reality with more than 45,000 million litres produced per year worldwide (REN21, 2020). In the USA, recycled feedstocks, mainly yellow grease, contributed 9% in 2020 to the national biodiesel production, equivalent to 651 million litres per year; this is 22% of the WCO generation potential estimated (U.S. EIA, 2020), as shown in Fig. 8. For other countries, the exact amount of recycled feedstock for biodiesel production remains unknown to the public.

The processing of WCO to biodiesel starts with eliminating food remaining particles by filtration or centrifugation. WCO drying is dependent on its water content; usually 2% of humidity is allowed. Commonly, if FFA content in WCO is less than 3%, the transesterification process proceeds directly (Popescu & Ionel, 2011). However, other authors considered even lower FFA values (Jeromin et al., 1987; Zhang et al., 2003). A higher FFA content indicates that an esterification step is required to prevent soap formation and, thus, decrease biodiesel yield.

Transesterification is the reaction of an ester with an alcohol, usually short-chain alcohol, such as methanol or ethanol. This reaction needs to be catalyzed to reach adequate conversion levels. Since vegetable oil is a mixture of triglycerides which are a tri-esters of glycerol, the reaction of these tri-esters with alcohol liberates glycerol molecule or its intermediates such as mono and diglycerides; among the factors that affect WCO conversion into biodiesel are the type and content of oil impurities (FFA, water, and oxidized matter), type and concentration of catalyst, alcohol to oil ratio, temperature, and stirring. Figure 9 shows a flow chart for direct transesterification of WCO.

Esterification is the reaction of a carboxylic acid with an alcohol in the presence of an acid catalyst to obtain an ester. Free fatty acids in WCO react with short-chain alcohol, such as methanol, in the presence of an inorganic acid, commonly

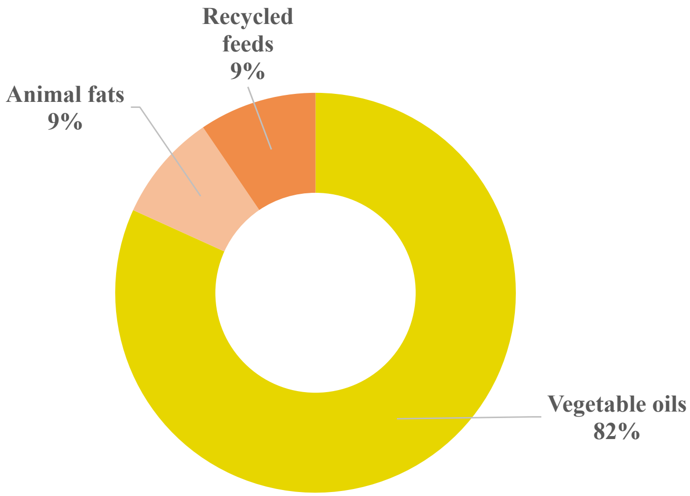


**Fig. 8** Biodiesel feedstocks in the USA, 2020. *Source* U.S. Energy Information Administration (2020)

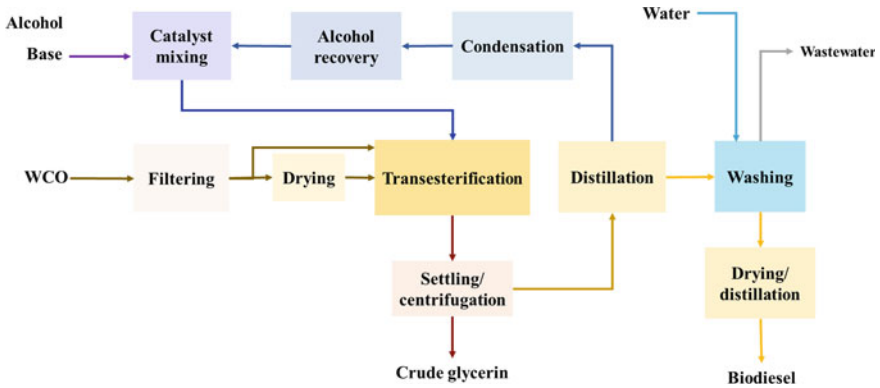


**Fig. 9** Process flow chart for direct transesterification of WCO, FFA <3%

sulfuric acid, to produce monoalkyl esters or biodiesel. Triglycerides are much less reactive and will not be converted under these conditions. Thus, they will be further reacted with methanol and a base to reach complete conversion of high FFA WCO feedstock into fatty acid methyl ester or FAME. Figure 10 shows a flow chart for esterification–transesterification of WCO.

WCO to biodiesel route is the less carbon-intensive path to obtain biodiesel that exists nowadays. Life cycle assessment of biodiesel production from different feedstocks showed that it reduces life cycle GHG emissions by 40–80% compared to petroleum diesel, where maximum reduction is for WCO biodiesel. Specifically, GHG emissions for petroleum diesel, VO biodiesel, and WCO biodiesel are shown

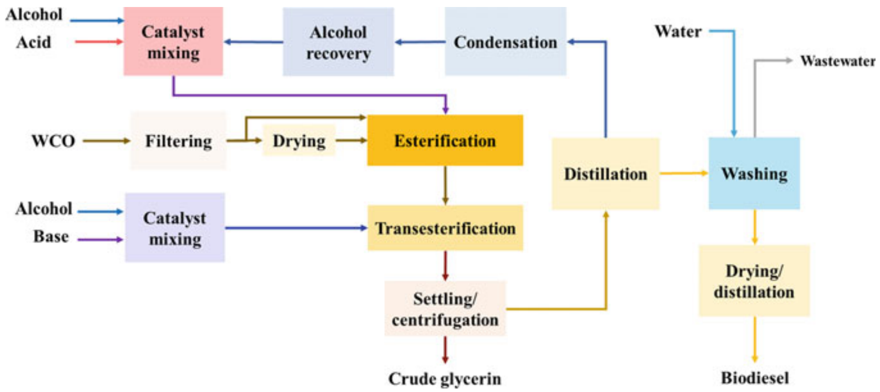


**Fig. 10** Process flow chart for esterification–transesterification of WCO, FFA >3%

**Table 4** Life cycle emissions for petroleum diesel, VO, and WCO biodiesels

| Fuel | Life cycle GHG emission (g $CO_2$ eq/MJ) | Life cycle GHG emission reduction (%) |
|---|---|---|
| Petroleum diesel | 87.1–92.0[b] | – |
| VO biodiesel | 40.0–50.1[a] | 47.0–57.0[a] |
| PO biodiesel | 46.3–75.7[a] | 19.0–51.0[a] |
| WCO biodiesel | 11.2–14.9[a] | 84.0–88.0[a] |

[a]EU Directive (2018); [b]Pleanjai et al. (2009)

in Table 4. The difference between WCO and VO derived biodiesel carbon footprint is due to the agricultural stage, which was not considered in the former case.

It is worth mentioning that these benefits depend not only on the inversion of natural resources and energy through the process but also on commercialization logistics. Thus, it would not be viable to consider a sustainable business model based on international trade for biodiesel, including its feedstocks, due to the GHG burden derived from overseas and air freight transportation. There are scarce studies considering the burden of international transportation of biodiesel feedstocks and finished products (Panichelli et al., 2009; Escobar et al. 2014). In this regard, ultimately, the decisions should be based on the LCA of the specific model.

## 8 Energy and Environment Policies

Nowadays, there are some negative incentives in countries that have not developed local biofuel industry and markets, to export feedstocks for biodiesel production, including WCO, mainly to EU countries whose policy support production of biodiesel based on waste or residual matter (EU Directive, 2018). Particularly under the double-counting policy, which was implemented as an incentive to achieve 10% of renewable contribution in the transport sector and states that waste-based biofuels can be counted twice (energy content) to calculate the contribution to renewable targets in transport (Drabik et al., 2019; Hammes, 2014).

One of these countries is Mexico which is not an oilseed producing country, so it imports this feedstock mainly from the USA. However, it is the twelfth largest consumer of VO (USDA, 2021), with an annual per capita WCO generation rate of 3.72 L, and is also the fourth petroleum diesel consumer in America with a per capita consumption of 175 L per year (British Petroleum, 2020; PEMEX, 2019).

The national legislation regarding the bioenergy industry was released in 2008, as the Law for Promotion and Development of Bioenergetics (LPDB, for its acronym in Spanish). However, blending mandates and tax incentives does not exist until today, and therefore, no formal framework exists to promote the national biodiesel program.

## 9 Mexico City Pilot

*Mexico City Generalities*

Mexico City is one of the world's megacities, with nearly 9.2 million inhabitants in an area of 1485 km$^2$ representing 6163.3 inhabitants per km$^2$, the highest in the country (INEGI, 2020). However, the Metropolitan Area of Mexico City (MCMA) agglomerates 21.8 million inhabitants, which makes this city the second-largest agglomeration in the Western hemisphere (only behind São Paulo in Brazil).

### *9.1 Waste Generation*

Waste generation in Mexico City ascends to 13,000 tons a year, with the economic and environmental cost for the city. Waste oils and fats have been considered in the law since 2015 through the environmental standard for the federal district NADF-012-AMBT-2015, establishing the conditions and technical specifications for the integral management of residual fats and oils of animal and vegetable origin in the territory of Mexico City.

Collecting companies exist in the city, but they are selling the WCO as feedstock to produce soap, animal feed, or biodiesel in other markets such as the USA and Europe. There is no regulation to blend biodiesel with petroleum diesel for the transport sector, so the investment in the biodiesel production industry is minimal and informal. In addition, tax credits or other kinds of incentives are absent, so fuel suppliers do not have any incentives to prepare blends. On the other hand, producers are not allowed to expend directly to the public, so their only possible market is companies having self-provision authorizations which is the only niche sector for formal producers.

As previously mentioned, Mexico has an interesting potential as a country to become a biodiesel producer, either from oily crops or WCO (Cortez-Núñez et al., 2020; Sheinbaum-Pardo et al., 2013). In the first stage, clearly, the most viable feedstock is WCO. As Mexico City is the largest and most densely populated urban area of the country, it constitutes the best scenario to run a pilot of a circular economy model to produce biodiesel.

## 9.2 The Transport Sector and Vehicle Matrix

According to the available energy matrix, Mexico City consumes basically secondary energy through petroleum fuels such as gasoline and diesel. In 2016, annual energy consumption was 385.2 PJ, from which 12.70% was diesel, equivalent to 1288 million litres per year (SEDEMA, 2018). The transport sector consumed 97.24% of diesel sold in the city. In this regard, according to official information, in 2016, 2,322,423 vehicles were circulating in the city; 148,584 of those were diesel with an average vehicular age of 13.2 years.

## 9.3 Sustainable City and Solar City Program

The Solar City program is aligned with sustainable energy and sustainable city strategies of the local government (CDMX Government, 2019). From the energy point of view, the main goals are related to the installation and operation of the biggest urban photovoltaic farm at the Central de Abasto (CEDA) of CDMX, the biggest wholesale market of Latin America, occupying an area of 810 acres. In this plan, the biodiesel program has been included. During 2020, a 0.2 MMgaly (800 gal/d) producing plant was installed within CEDA's area with the Secretary of Education, Science, Technology, and Innovation (SECTEI) funding. The plan is to produce biodiesel from WCO by taking advantage of the experience and infrastructure of collection companies operating in CDMX for several years.

Consumption of WCO biodiesel is planned for public transport to impact decarbonization efforts from the local government towards 2025 positively. This is the first effort in Mexico that covers all sustainability edges in an integrated and fully coordinated manner under the leadership of local authorities.

The goal of the program is to produce 2.1 million litres of biodiesel per year by 2024. Formally installed capacity at this moment is approximately 50% of this target. Given the current energy policies in Mexico, the importance of such a pilot program is determining for short and medium terms the fate of the biofuel industry in the country.

### *9.4 Circular Model of Biodiesel Production of WCO in Mexico City*

As previously mentioned, WCO biodiesel represents the highest opportunity to reduce GHG emissions from the transport sector in urban areas, reaching up to ~88% diminishing. This is particularly feasible due to the life cycle assessment rules that exempt waste and residual feedstocks from the environmental burden, starting to count them at the starting of the valorization process.

Figure 11 shows the circular model for biodiesel production in Mexico City. The first stage represents a linear model for vegetable oil production, consumption, and disposal. Vegetable oil arrives in the city to be consumed by previously mentioned sectors (industry, services, and household), and waste is generated at these locations, becoming waste sources. Theoretically, all these sources must perform controlled disposal of WCO and animal fats in the city, according to NADF-012-AMBT-2015. However, in practice, there is still an undetermined amount of WCO and animal fat that is disposed of through sewage, water bodies, or to uncontrolled alternative valorization routes such as animal feed formulation or products for human use such as soap, even more, uncertainty exists on the amount of WCO that is exported to foreign countries as recycled feedstock. Even though potential reserves of WCO in the city ascend to 0.034 MMton per year, local authorities have determined proved reserves for 3.6 Mton per year, i.e. 10.58% of potential estimated. Even though the possibility to capture these reserves constitutes an annual reduction of c.a. 13,200 tons-eq of $CO_2$, without considering transport $CO_2$ burden from the transportation of petroleum diesel, because Mexico imports 66% of its consumption (PEMEX, 2019). Regarding water pollution, recycling 4 million litres of WCO would avoid the contamination of ~170 $MMm^3$ of water (SEDEMA, 2020). As previously mentioned, the goal towards 2024 is to reach a production of 2.1 million litres of biodiesel, representing mitigation of 6900 tons of $CO_2$ eq and avoiding the pollution of 84 $MMm^3$ of water. CEDA's plant contributes ~50% of this goal.

In this pilot program, stakeholders are local government, academic institutions, and private entities to maximize social and environmental benefits. The local government has set the legislation base for the recycling of WCO and fat and further has invested through the SECTEI to fund the construction of the plant, based on a technology developed by the National Polytechnic Institute (IPN) who is also the technological assessor of the project (IPN, 2020). Private companies participate in the collection and operation of the production facility.

### *9.5 WCO Collection*

Collecting of WCO is planned to be a hybrid model operated by companies already working in the city in parallel with a public social model that will start to operate through donating/recycling points at local public markets, where citizens will be

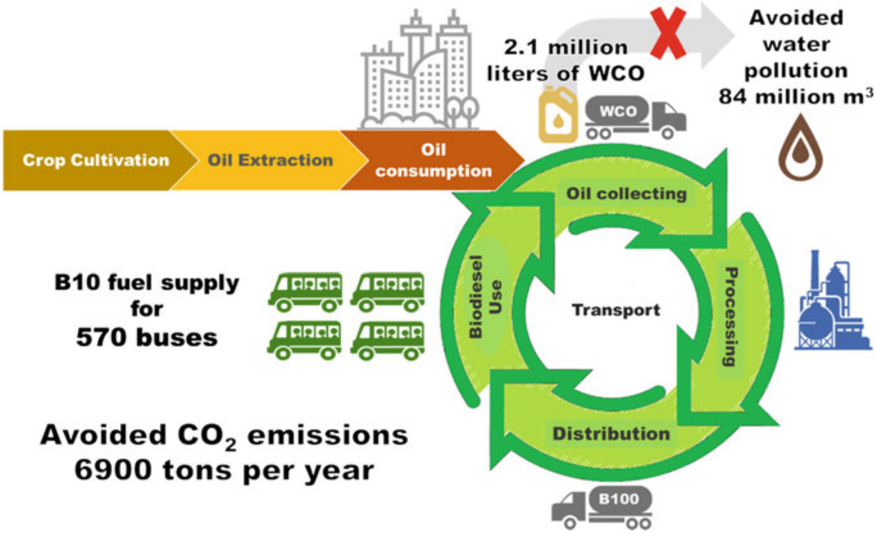


**Fig. 11** Circular model for biodiesel production in urban areas

able to donate household generated WCO. Thus, accordingly to the classification of recycling modes, the Mexico City model will be a third-party take-back (TPT) for services and industrial sector and a manufacturer take-back model (MTB) for public markets and donating points (Zhang et al., 2014).

Currently, public markets and food preparation small businesses have already started to donate to the biodiesel program. Collection figures will be confirmed by the term of the first year of operation (2021). At present, the price of locally recollected WCO ascends to 10–12 MXP per kg, about 0.23–0.28 USD per pound. Additional incentives for public recollection are desirable to increase citizens collaboration and more strict controls for medium and major generators. Although now no subsidies are considered for biodiesel producers, in the case of the pilot case, the government support will be the promotion to sell all the CEDA's plant production to public transport companies.

## *9.6 Processing*

Processing of WCO can be divided into primary, equivalent to feedstock conditioning, and secondary, which corresponds to transformation into biodiesel through transesterification or esterification–transesterification scheme, depending upon impurities content in WCO, mainly particles, water, and FFA.

CEDA's biodiesel plant operates with local technology IPN-GBD-1000© developed by public university Instituto Politécnico Nacional (Hernández-Altamirano & Mena-Cervantes, 2018). The technology is based on a green inspired process that

**Fig. 12** CEDA's biodiesel plant IPN-GBD-1000© technology. *Source* Mexico City Government (2020)

follows both green chemistry and cleaner production principles, summarized as follows:

- Zero waste or total valorization
- Zero water waste
- Zero energy waste or maximal energy output.

Environmental footprints through the processing stage are commonly ignored or considered of low impact. Therefore, it is important to have traceability of the environmental impacts associated with the processing or transformation stage, especially in countries starting to promote the biofuel industry. In this regard, IPN-GBD-1000© technology can help to acquire an ecoefficiency approach from the beginning as early adopted sustainable technology, setting a precedent for future projects (Fig. 12).

## *9.7 Distribution and Use*

CEDA's plant is located on the eastern side of the city, within the biggest wholesale market of Latin America. Figure 13 shows a map to locate CEDA's facilities in Mexico City, and it can be observed that important places are located within a radius of 7 km, such as the city's downtown and the international airport. Public transport modules are also located close to CEDA, within a 7 km radius. Thus, biodiesel

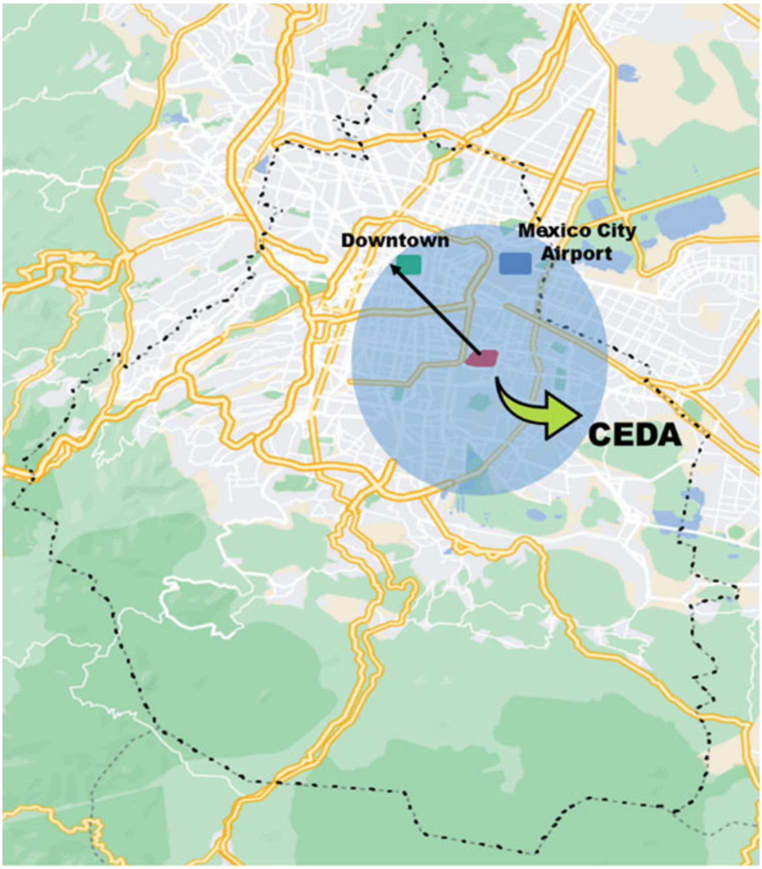


**Fig. 13** Important commercial and transport centres within a radius of 7 km around CEDA

produced at the CEDAs plant could be distributed relatively easily to public and private fuel suppliers, as shown in Fig. 13.

## *9.8 Use*

The local government has made public its plans to use the biodiesel produced at CEDA's plant for public transport. Targets are local public passengers transport companies managed by the government, particularly Passenger Transport Network (RTP, by its abbreviation in Spanish) and the System of Public Passenger Transport Corridors, known as Metrobus, which are emblematic lines of public transport in the city. Figure 14 shows a Metrobus vehicle participating in the pilot.


**Fig. 14** Metrobus vehicle running on biodiesel blend during the pilot. *Source* SEMOVI-CDMX

These buses consume diesel fuel at a rate dependent on the specific route. However, a typical value could be set at 100 L per day for a route of approximately 200 km (Sheinbaum et al., 2015). Considering a B10 program, CEDA's plant could supply c.a. 300 buses operating at full capacity (each bus consuming 10 L per day of B100). The use of WCO biodiesel in public transport busses has an additional advantage consisting in generating the lowest emission factor per capita given that GHG mass is divided among the passengers in the bus, often around 40 passengers on the route.

Additional benefits would arise from diminishing PM, HCs, and CO emissions typically associated with diesel engines, as previous studies have reported (Sheinbaum et al., 2015; USEPA, 2002). The decrease is directly proportional to the amount of biodiesel in the blend. Thus, for B10 blend in EPA-04/EURO IV (or more recent) vehicles, emission reductions would be of 60, 32, and 4.5% for PM, CO, and $NO_x$, respectively (Sheinbaum et al., 2015).

## 10 Perspectives and Conclusions

WCO is a sustainable feedstock for biodiesel production, representing a measure to mitigate GHG emissions, reducing up to 88% of GHG emissions compared to petroleum diesel. Furthermore, it is recycling to produce biofuel avoids environmental and health risks such as sewage obstruction, water pollutions, and uncontrolled disposal. WCO best circular model should be based on local collection and processing. Otherwise, economic and social benefits are triggered by pure market incentives such as animal feed formulation and exportation to foreign countries. The role of public policies is of the highest importance to trigger the development of the biofuel industry in countries that have not developed a biofuel industry, such as Mexico. A pilot program of biodiesel production-consumption in Mexico City is the only current project of bioenergy in the country.

It is expected that this model maximizes the environmental, economic, and social benefits from the production of biodiesel since the four steps of the life cycle system would be located within the city in one of the highest populated and more commercial areas, minimizing transport and distribution burdens while keeping environmental, social, and economic benefits for the local population.

SARS-COV-2 pandemic has slowed down the execution of the program. However, several batches of biodiesel have been produced, and consumption trials have begun in public transport vehicles. Once the first year of the pilot has finished, it would be desirable to perform an LCA for the case to fully evaluate de environmental impacts and benefits of the pilot program.

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# Circular Economy Involving Microbial Consortia in Consolidated Bioprocesses to Produce Biofuels

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## 1 Introduction

World energy consumption in 2015 was 552.2 exajoules, equivalent to 13,147.3 million tons of oil, corresponding to 78.4% fossil fuels, 2.3% nuclear energy and 19.3% for renewable energies (i.e., 14.1% biomass from the renewable total), while global energy demand has increased by 4.6% in 2021 (IEA, 2021). Biofuels are found within biomass with 0.8% of the total percentage, where bioethanol is the main fuel with 0.059% of the energy consumed this year, equivalent to 74% from the total of biofuels, highlighting a high production and consumption worldwide (Alaswad et al., 2015).

Biofuels are classified according to the type of biomass used as raw material (Fig. 1): primary, secondary, tertiary and fourth generation. The primary ones are obtained directly from unprocessed biomass (e.g., maintaining their natural chemical structures) edible crops such as sugar cane, corn and wheat, where bioethanol and biodiesel stand out. Secondary ones are generated from the processing and transformation of lignocellulosic biomass and different organic residues by the action of microorganisms (Ambaye et al., 2021). Third-generation biofuels are based on

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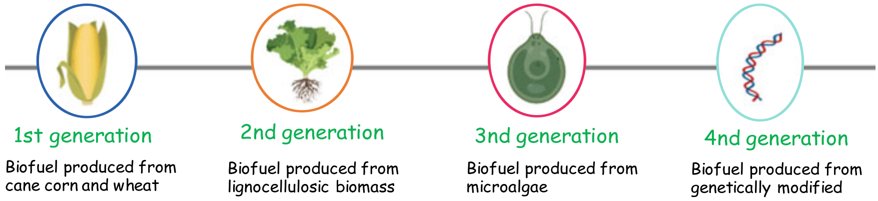


**Fig. 1** Advances in biofuels

marine biomass, mainly algae, producing a significant amount of lipids and carbohydrates to produce biodiesel and bioethanol. Advantages of this process involve a direct growth of algae from carbon emission sources, which are subsequently turned into fuel without $CO_2$ emissions, and the cultivation of microalgae is very short with an accelerated growth rate. The fourth generation of biofuels depends on the genetic modification and metabolic pathways of the microorganisms responsible for fermentation (Alam et al., 2015; Alaswad et al., 2015; Nigam & Singh, 2011). Figure 2 summarizes the different processes of biofuel production from the first to the fourth generation (Ambaye et al., 2021).

In this context, the application of the circular economy has positioned as one of the pillars in a sustainable form for energy security, through various lignocellulosic materials to biotransform them into a variety of high-value compounds such as biofuels, which remarkably decrease the costs to obtain bioenergy, and environmental pollution such as the generation of greenhouse gases (Bilal & Iqbal, 2019).

## 2 Food Losses and Waste as Renewable Raw Materials in the Circular Economy for Biofuel Production

Lignocellulose biomass is the most abundant renewable resource in the world, considered a sustainable, available, economical and promising raw material to produce biofuels. The composition of lignocellulosic biomass is typically cellulose (30–45% wt.%), hemicellulose (15–30% wt.%), and lignin (12–25% wt.%). The first step in the bioconversion of lignocellulosic biomass is the removal of lignin and the cellulose breakdown through a chemical or enzymatic pretreatment. Subsequently, the enzymatic saccharification converts them into sugars to generate many valuable products such as ethanol and many other products using microbial catalysts (Parisutham et al., 2014).

Another type of biomass recently valued within the circular economy is food losses and waste (FLW), which are classified as renewable raw materials and generated in the different stages of consumption. FLW is attractive to yield biofuels given the abundant volumes annually generated, their null competence with food and high content of lignin, proteins, carbohydrates, lipids, cellulose, and hemicellulose. They

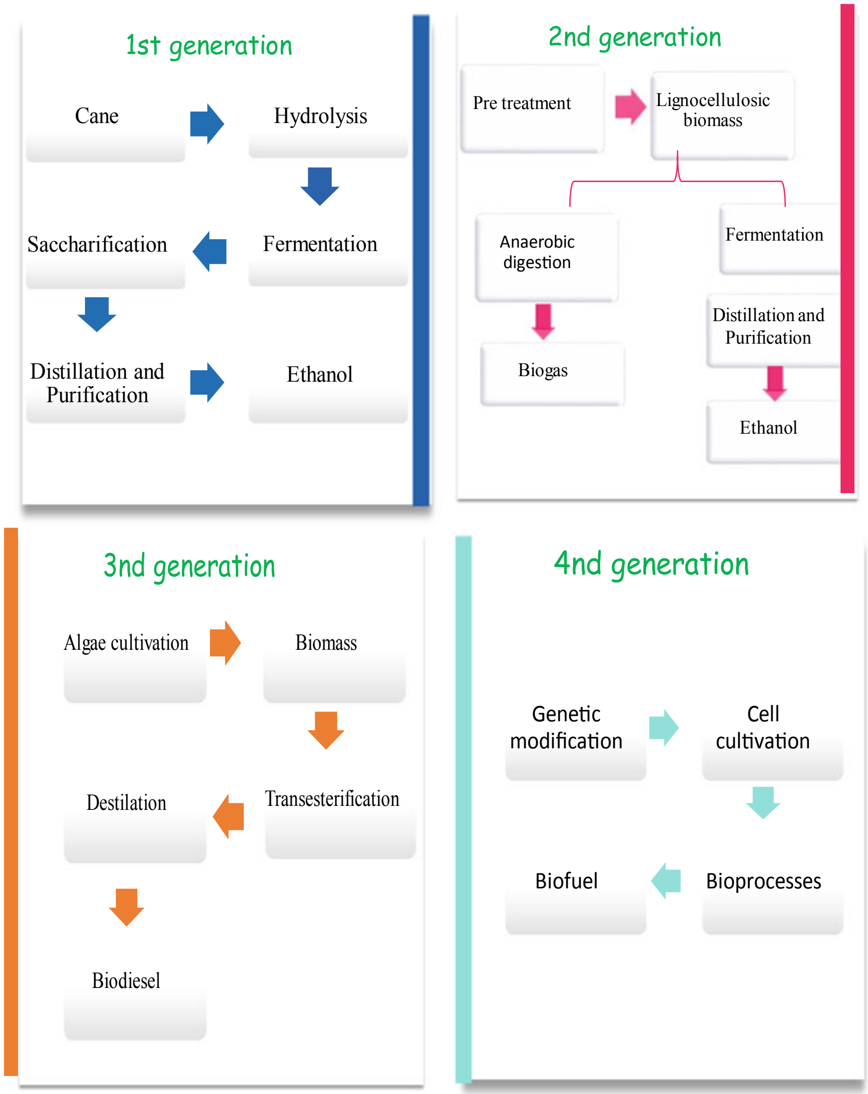


**Fig. 2** Biofuel generation strategies (adapted from Ambaye et al., 2021)

can often serve as cheap sources of carbon and nitrogen for the growth of microorganisms, which make them viable to be applied in a biorefinery. This minimizes the use of virgin resources and eliminates the need for treatment and transport of FLW through the 3Rs implementation action plan, contributing to the sustainable development goals established for the 2030 agenda: efficient conversion of biomass, use of renewable materials at industrial levels and food waste minimization, through sustainable agricultural production and food security (Awasthi et al., 2020; Beretta &

Hellweg, 2019; Carmona-Cabello et al., 2020; Schütte, 2018). In this context, the 2020 European Strategy for smart, sustainable and inclusive growth indicates that the circular economy is a key strategy to achieve this; although the reduction, reuse and valorization of FLW for biofuel generation are at the early stages of the investigation, but it will certainly have a positive impact on the economy, food security and the environment. Likewise, the carbon dioxide released when lignocelluloses are burned is offset by the total volume reinstated from the cultivation of plants as a successful business model (Fig. 3) (García-Solares et al., 2021; Zabaniotou & Kamaterou, 2019).

FAO defines food losses and waste (FLW) as "the loss of quality and quantity of food through numerous processes taking place in the supply chain like production, post-harvest and processing stages". Every year, 1.3 billion tons of food worldwide is wasted, disposing of large volumes of waste in landfills. The main FLW generated by agricultural resources is rice, sugarcane bagasse, vegetable wastes, food products, wheat straw with shell, jute fiber, peanut shells and cotton stem with coconut shell. The most important objective of the management and valorization of FLW is to maximize financial returns and the protection of the environment (Awasthi et al., 2020; Mak et al., 2020). Food waste can be classified into avoidable (edible) and unavoidable (inedible) as bones, seeds, shells, fruit and vegetable shells. These wastes are influenced by geography, cultural and socioeconomic factors; for instance: some parts of the chicken such as offal and legs are consumed in some supply chains of food, but not in others whereby they can be used as a renewable raw material in the generation of biofuels and other value-added bioproducts (García-Solares et al., 2021; Mak et al., 2020; Sarsaiya et al., 2019; Van Der Werf & Gilliland, 2017). Some examples of the use of FWL in biorefineries have involved their characterizations in the restaurant sector (Carmona-Cabello et al., 2020), the use of FWL coffee in a

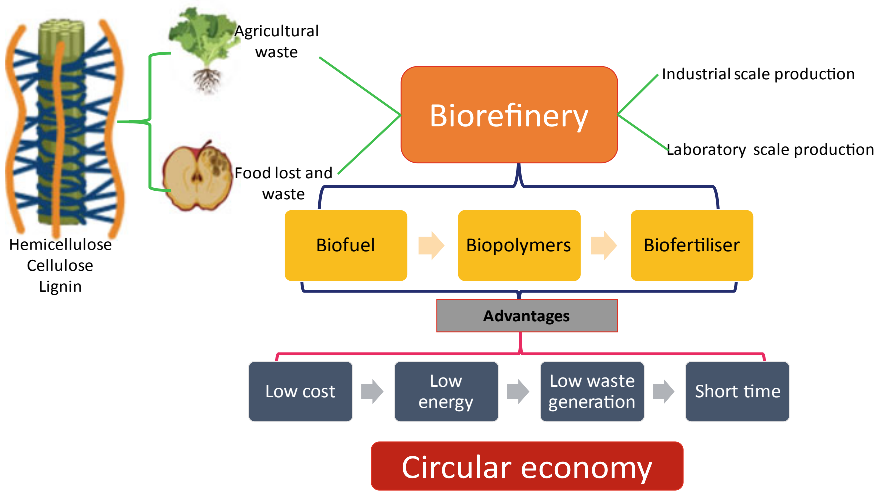


**Fig. 3** Importance of biomass in the circular economy (adapted from Sarsaiya et al., 2019)

biorefinery for biofuel production (Zabaniotou & Kamaterou, 2019) and wastes of citrus peels as a promising and sustainable option to generate bioethanol due to its low lignin content (Jeong et al., 2021). It is estimated that by 2030, the total biomass supply worldwide will range from 97 to 147 EJ/year, which will remarkably be raised by 2050, where agricultural residues will continue to be the largest supply of biomass, providing up to 550 EJ/year (Ambaye et al., 2021).

## 3 Biofuels in the Circular Economy

It is important to mention that biomass constitutes one of the main sources of renewable energy, contributing with 10–14% of the world's energy supply, whereby there is a great interest that biofuels can be obtained through biomass due to the fact that they can be used as alternatives to fossil fuels (Guo et al., 2015). Biomass constitutes the restoration cycle considered exclusive to this raw material, whence a large part of the waste generated from bioprocesses contributes to the formation of new biomass, which is incorporated naturally into the carbon cycle without generating an imbalance since the amount of $CO_2$ generated is absorbed by the lignocellulosic matter (Kishor et al., 2021; Sherwood, 2020).

Biofuels derived from biomass are obtained through physical, chemical, biological or thermal processes in solid, gaseous and liquid states (Guo et al., 2015; Rodionova et al., 2017). Solid biofuels are generated through mechanical processes, mainly compacting wood and its wastes, to make briquettes and pellets commonly used in boilers (Angulo-Mosquera et al., 2021). Currently, the most widely used gaseous biofuels are biogas and biohydrogen. Biogas is produced using solid waste as raw material, either from animals or food, through a fermentation process made up of several stages, including hydrolysis, acidogenesis, acetogenesis/dehydrogenation and methanization to obtain mainly methane ($CH_4$) and carbon dioxide ($CO_2$) with the percentage ranging from 60 to 70% and 30 to 40%, respectively. Other subproducts include carbon monoxide (CO), ammonium ($NH_4$), oxygen ($O_2$), nitrogen ($N_2$), and ammonium sulfite ($(NH_4)_2SO_3$) (Antwi et al., 2017; Cruz-Salomón et al., 2017; Saastamoinen et al., 2021).

Hydrogen production comes from raw materials such as organic compounds or water through conventional and biological processes (Fig. 4). The electrolysis of water is a conventional electrochemical process conducted in an electrolyzer that contains an anode and a cathode where water is dissociated using an electric current (Chi & Yu, 2018). Hydrogen can also be produced by means of steam reforming consisting of a packed bed reactor at temperatures ranging between 500 and 900 °C and pressures greater than 20 bar, although this may vary depending on the hydrocarbon used (Acar & Dincer, 2018; Parkinson et al., 2017). Hydrocarbons are used as a raw material in the partial oxidation generating hydrogen, mainly natural gas, which is subjected to a large amount of pure oxygen at temperature and pressure depending on whether the reactor is operated with a catalyst or not. If catalysts are not used, the temperatures used range from 1200 to 1500 °C with pressure from 25 to 80 bar; otherwise, the temperature will be from 800 to 900 °C at a pressure from 25 to 35 bar. The catalysts are regularly made of precious metals such as nickel or cobalt (Acar & Dincer, 2018; Sengodan et al., 2018). Hydrogen production through gasification is a process where combustible materials are exposed at temperatures from 800 to 1500 °C to a gasifying agent such as air, oxygen, carbon dioxide, among others. The amount of gasifying agent used in the process depends on the amount of raw material used, as well as the composition of the desired gas (Acar & Dincer, 2018).

The biological production of hydrogen can be conducted via biophotolysis or fermentation. Biophotolysis does not generate greenhouse gases, making it a sustainable and useful process for the circular economy. This process is based on the dissociation of water by means of photosynthetic microorganisms such as cyanobacteria or green algae, the presence of oxygen in this process must be limited; otherwise, it can damage the hydrogenase enzyme causing low hydrogen production efficiencies. This process is divided into two groups, known as direct and indirect biophotolysis (Dinesh et al., 2018). Direct biophotolysis uses water to dissociate it into oxygen and hydrogen through the nitrogenase and hydrogenase enzymes found in cyanobacteria and microalgae (Table 1) (Arimi et al., 2015; Aslam et al., 2018; Dinesh et al., 2018). Indirect biophotolysis takes place in two steps: (i) microorganisms convert carbon dioxide to carbohydrates, (ii) which are subsequently fermented to produce hydrogen in the presence of light. The microorganisms that generally carry out this process are cyanobacteria (Arimi et al., 2015). The fermentation process can be carried out using light, dark or a combination, with a great variety of plant residues and FWL as a substrate to produce hydrogen. Likewise, the microorganisms participating in this process are varied (Table 2) (Gomez-Romero et al., 2014; Uçkun Kiran et al., 2014).

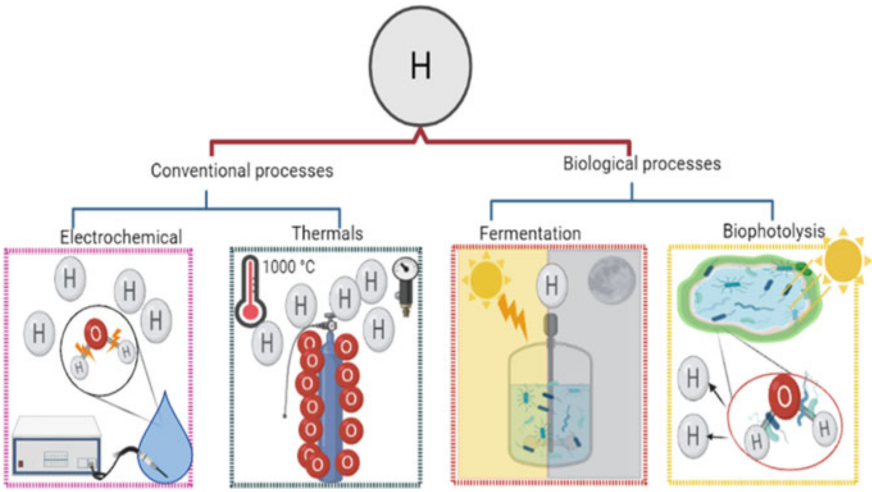


**Fig. 4** Production hydrogen processes

**Table 1** Microorganisms from biophotolysis

| | Biophotolysis | | | | | | |
|---|---|---|---|---|---|---|---|
| | Microorganisms | Carbon source | pH | Temperature (°C) | Light intensity | Type of process | References |
| Green algae | *Chlorella sorokiniana Ce* | Acetate | NR | NR | 120* | Batch | Chader et al. (2009) |
| | *Chlamydomonas reinhardtii* | Air | 7.8 | 27 | 150* | Batch | Oncel and Kose (2014) |
| | *Chlorella sp.* | Glycerol | 6.8 | NR | 48* | Batch | Sengmee et al. (2017) |
| | *Platymonas subcordiformis* | Water and glucose | NR | NR | 5000 lx | Batch | Dudek et al. (2018) |
| Cyanobacteria | *Aphanothece montana* | Air | NR | NR | 4–6 $W/m^2/s$ | NR | Dasgupta et al. (2010) |
| | *Anabaena sp. PCC* 7120 | RN | NR | 25 | 240, 384, 678 W | Batch | Ferreira et al. (2012) |
| | *Lyngbya sp.* | Benzoate | 7.4 | 32 | 4000 lx | Batch | Shi and Yu (2016) |

Light fermentation or photofermentation is a process in which photosynthetic bacteria, mainly purple non-sulfur bacteria (PNS), convert organic compounds, such as volatile fatty acids, into hydrogen and carbon dioxide using light as an energy source (Aslam et al., 2018; Dinesh et al., 2018). In the case of dark fermentation, the bacteria are strict anaerobes that can transform organic and inorganic compounds to hydrogen, carbon dioxide and some secondary metabolites (e.g., organic acids and alcohols). One important drawback of dark fermentation is the low efficiency when converting organic compounds to hydrogen; nevertheless, it is frequently used because it does not require lighting in the process, which reduces the operating costs (Aslam et al., 2018; Dinesh et al., 2018).

Fossil fuels are intended to be replaced mainly by liquid biofuels such as bioethanol (Nigam & Singh, 2011). Ethanol has taken relevance from September 2018 to August 2019, exceeding 16.93 billion gallons. However, the production increasing was relatively slow, probably due to challenges associated with production, transportation, storage, government policies and blends of ethanol with gasoline (Ambaye et al., 2021). The main stages of ethanol production are: (i) pretreatment involving the separation or solubilization of the raw material components to facilitate the subsequent stages, (ii) hydrolysis, where the biopolymers are transformed into sugars, (iii) fermentation being the most important above described and (iv) recovery of the product (Zabed et al., 2017). Figure 5 shows a general diagram of bioethanol production by fermentation using different substrates.

**Table 2** Hydrogen-producing microorganisms through fermentation

| | Microorganisms | Carbon source | pH | Temperature (°C) | Light intensity | Type of process | References |
|---|---|---|---|---|---|---|---|
| Photosynthetic | *Rhodobacter capsulatus* | Acetate | NR | NR | 90 | Batch | Boran et al. (2010) |
| | *Rhodopseudomonas capsulata* | Benzoate Glutamate | 7 | NR | 4000 lx | Batch | Shi et al. (2014) |
| | *Rhodopseudomonas sp. nov. Strain A7* | Acetate | 6.86 | 35 | 150 | Batch | Wen et al. (2017) |
| | *Rhodobacter sphaeroides* MDC6521 | Acetate, Malate, Succinate | 7.5 | 30 | 200* lx | Batch | Hakobyan et al. (2019) |
| Anaerobic | *Enterobacter cloacae* IIT-BT 08 | Distillery wastewater | 7.5 | 37 | NA | Batch | Mishra and Das (2013) |
| | *Clostridium sp.* YM1 | Glucose | 6.5 | 37 | NA | Batch | Abdeshahian et al. (2014) |
| | *Thermoanaerobacterium thermosaccharoliticum* KKU19 | Hydrolyzed palm oil | 6.7 | 54.4 | NA | Batch | Sitthikitpanya et al. (2017) |
| | *Clostridium butyricum* CWBI1009 | Glucose | 7.3 | 30 | NA | Batch | Hamilton et al. (2018) |
| Combined | *Clostridium butyricum* *Rhodopseudomonas feacalis* RLD-53 | Glucose | 7 | 35 | 10.25 | Batch | Liu et al. (2010) |
| | *Enterobacter aerogenes* *Rhodopseudomonas* BHU 01 | Cheese whey | NR | 30<br>34 | 8 | Batch | Rai et al. (2012) |
| | *Clostridium butyricum LS2* *Rhodopseudomonas palustris* | Palm oil wastewater | 5.5<br>7 | 30 | 100* W | Batch | Puranjan Mishra et al. (2016) |
| | *Clostridium acetobutylicum* *Rhodobacter sphaeroides* | Acetic and butyric acid | 5.5<br>7.5 | 32 | 193 | Batch | Zagrodnik and Łaniecki (2017) |

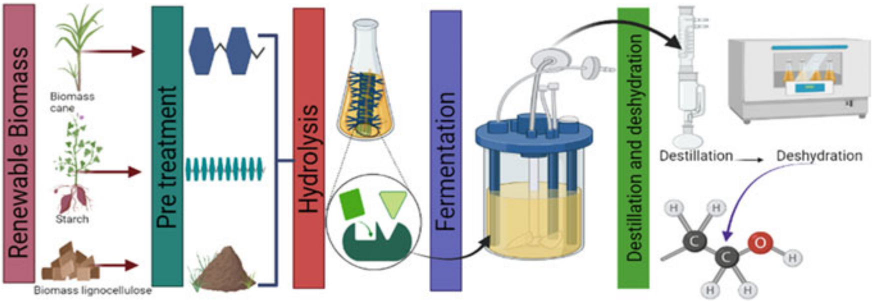


**Fig. 5** Renewable biomass treatment

Pretreatments can be classified according to their mechanisms of action and impact on biomass as: physical, chemical, biological, physicochemical and a combination. It is important to mention that the choice of an appropriate pretreatment is beneficial since it brings an increase in the performance and productivity of the process, which is reflected in the overall efficiency (Karimi & Taherzadeh, 2016).

The hydrolysis process can be carried out by two mechanisms: chemical and enzymatic. Chemical hydrolysis consists of using acids and bases as catalysts to transform the polysaccharide chains present in biomass into elemental monomers, that is, reduction and fermentable sugars. This involves considering the type and concentration of acid and base, temperature, pH, biomass sample and time. The acid-catalyzed hydrolysis of cellulose to produce glucose presents three steps: (i) protonation of glycosidic oxygen, (ii) cleavage of the glycosidic bond and (iii) nucleophilic attack of water. Alkaline hydrolysis is the saponification process of the ester bonds of hemicellulose and xylan (Achinas & Euverink, 2016). The yield to obtain sugar through the fermentation process will depend on the hydrolysis conditions and the type of biomass used as raw material. The main limitations of chemical hydrolysis are the generation of solid waste, the increase in biofuel production costs and the generation of toxic residues that are inhibitors of fermentation found in hydrolysates, such as acetic acid, formic acid, levulinic acid, furaldehyde 2-furaldehyde (furfural), 5-hydroxymethyl-2-furaldehyde (HMF), phenols and huminis (Fig. 6) (Guo et al., 2015). This last one considers unwanted products since the carbon in cellulose is transformed into humins and embedded in the reactor, thus reducing the efficiency of fermentable and reductor sugars in ethanol production (Kang et al., 2018). The chemical hydrolysis process is not sustainable due to this condition, representing a challenge in the incorporation of the circular economy, although renewable materials are used to obtain sugars, and efforts are currently made for its sustainable implementation (i.e., dilutions with acid) (Kang et al., 2018).

Enzyme hydrolysis is more effective than the chemical route since enzymes are very specific in the activities they perform. Cellulases are divided into three large groups: (1) endoglucanases, attacking the regions of low crystallinity of cellulose, leaving the ends of the chains free, (2) exoglucanases, hydrolyzing cellulose forming cellobioses, and (3) β-xylosidases, converting cellobiase residues in glucose residues.

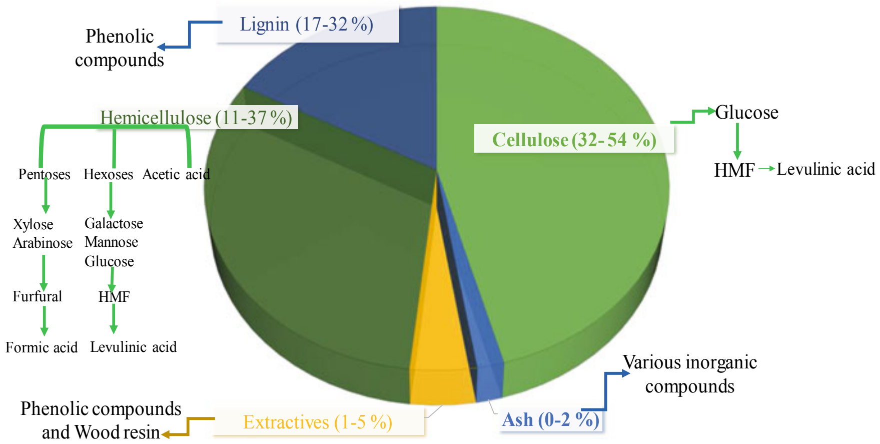


**Fig. 6** Composition of lignocellulosic materials (adapted from Guo et al., 2015)

Cellulases are produced by bacterial and fungal routes. It has been discovered that the mechanism of accessibility of the enzyme to the raw material is through the pores of the cell wall during hydrolysis, which influences the efficiency of the hydrolysis process (Liu et al., 2019a, 2019b). The use of enzymes is limited by the temperature control, their isolation costs, purification and recovery (Liu et al., 2019a, 2019b). The pretreatment of lignocellulosic materials is required in biorefineries to reduce the cellulose crystallinity, increasing the porosity of the biomass and improving enzymes accessibility. In general, the pretreatment should minimize the carbohydrates losses, formation of by-products and inhibitory compounds (Sun & Cheng, 2002).

Extensive scientific research identifies the following fermentation strategies, which are classified according to hydrolysis stages (Fig. 7): (a) separate hydrolysis and fermentation (SHF), (b) simultaneous saccharification and fermentation (SSF), (c) saccharification simultaneous and co-fermentation (SSCF) (Paulová et al., 2015) and (d) consolidated bioprocesses (CBP) (Fan, 2014; Lynd et al., 2005; Parisutham et al., 2014; Paulová et al., 2015).

SHF consists of carrying out two operations consecutively. First, the enzymatic hydrolysis metabolizes sugars by the selected fermenting microorganism to be transformed into ethanol. The advantage of this configuration is the possibility to be carried out under optimal process conditions when carried out in different reactors (e.g., temperature, pH, and nutrient concentration), thus improving productivity (Fig. 7a) (Paulová et al., 2015).

SSF integrates the enzymatic hydrolysis of the pretreated lignocellulosic material and the fermentation of sugars in a single reactor. Accordingly, sugars are rapidly consumed and metabolized by fermenting microorganisms, efficiently eliminating or reducing the effect of glucose inhibition on celluloses since it does not accumulate in the culture broth. This remarkably reduces the residence time and achieves higher ethanol yields compared to SHF (Paulová et al., 2015). An important advantage is

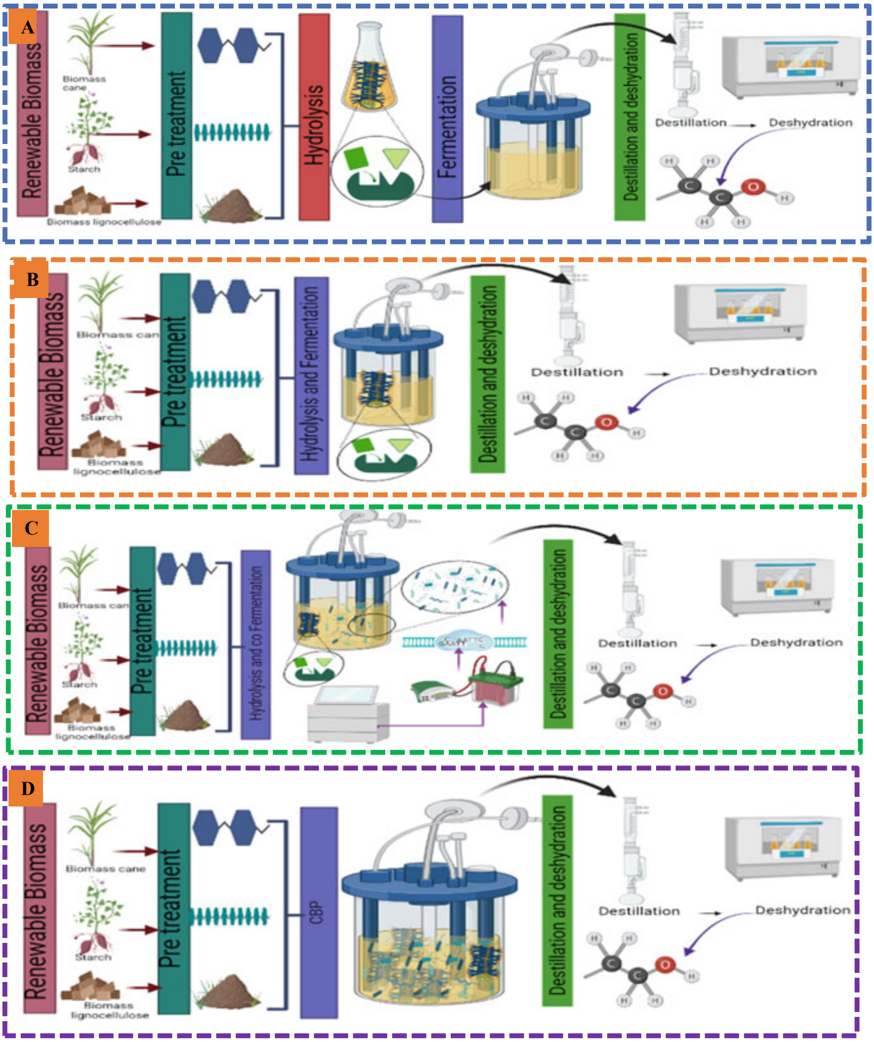


**Fig. 7** Fermentation strategies (adapted from Fan, 2014; Parisutham et al., 2014)

that the risk of contamination decreases by enhancing the process in a single reactor, whence a lower investment is required (Fig. 7b).

SSCF consolidates enzymatic hydrolysis and fermentation in one step due to advanced engineering techniques allowing the microorganism to co-ferment pentoses and hexoses. SSCF can achieve higher product yields, lower operating costs, and higher process efficiency compared to SSF (Fig. 7c) (Fan, 2014).

*Saccharomyces cerevisiae* yeast is the most attractive option among the microorganisms used and studied as fermenters since, in addition to complying with performance, efficiency, productivity and tolerance to ethanol, it has the ability to produce flocs during growth, facilitating the sedimentation and suspension of the bacteria, which benefits the production (Zabed et al., 2014). Other widely studied microorganisms for ethanol production are *S. diastaticus*, *Kluyveromyces marxianus*, *Pichia kudriavzevii*, *Escherichia coli*, *Klebsiella oxytoca* and *Zymomonas mobilis* (Table 3) (Zabed et al., 2014). The main disadvantage of ethanol production with pure strains is the requirement of controlled conditions for their development, such as pH, temperature, specific nutrients and sterile conditions.

CBPs are at an early stage of research and application; however, they have proven to be an efficient technology for the generation of biofuels and application in biorefineries, being a significant alternative in the circular bioeconomy. They have been proposed as an alternative to conventional hydrolysis and fermentation methods since they combine all the stages of biofuel production in a single reactor or the direct bioconversion of lignocellulosic biomass to biofuels, namely the production of enzymes, hydrolysis enzymatic and fermentation are carried out in one step. The main advantages of CBP are the low costs, the processing time, the diversity of lignocellulosic biomass that can be used as a substrate for the release of sugars, where none of them is used for the production of cellulose, and the reduction of energy consumption and inputs (Fig. 7d) (Rastogi & Shrivastava, 2017).

## 4 Biofuel Production with Native Microbial Consortia: Innovation in the Circular Economy

Consortia, also called co-cropping and mixed-cropping, are a diverse set of species that do not only coexist together but often with complementary metabolic functions and diverse relationships, such as mutualism, commensalism, parasitism or predation, competition and neutralism, where difficult tasks can be divided among numerous organisms and microorganisms to obtain a product (Fig. 8) (Jia et al., 2016; Peng et al., 2018).

In general, a consortium works through cross-feeding; that is, the metabolites produced by some microorganisms are used by another individual(s), resulting in the evolution of a member of the consortium to start producing more and more quantities of a certain metabolite for the benefit of other members. Figure 9 schematizes cross-feeding: (A) Division and expansion of resources (beneficial interactions), (B) Cooperation during this process can develop microbial metabolism, (C) Improved tolerance of inhibitors, (D) Competition for the substrate is directed toward a beneficial production of metabolites and enzymes that cannot be produced otherwise and (E) Assembled biotransformation pathway to optimize efficiency, generating a new metabolic pathway to continue with the process within the consortium (Zhang et al., 2018).

Cross-feeding has been studied in modern biotechnology to produce bioproducts (Moreno-García et al., 2021; Valdez-Vazquez & Sanchez, 2018), water and soil remediation (García-Solares et al., 2013, 2014; Reyes-Romero et al., 2021).

**Table 3** Fermenting microorganisms

| Microorganisms | Substrate | Configuration | Temperature (°C) | pH | Agitation (rpm) | Efficiency (%) | Productivity (g $L^{-1}$ $h^{-1}$) |
|---|---|---|---|---|---|---|---|
| *K. marxianus DMKU 3-1042* | Cane | Batch | 40 | 5 | 300 | 60.4 | 1.42 |
| *P. kudriavzevii* | | Batch | 40 | 5.5 | 150 | – | 4 |
| *S. cerevisiae* | | Batch | 30 | – | – | – | 2.48 |
| *K. marxianus DMKU 3-1042 y S. cerevisiae M30* | | Batch | 37 | 5 | 150 | 80.23–86.1 | 1.07 |
| *Strain Saccharomyces sp.* | | Continuous | 30 | 5 | – | 80.4–97.3 | – |
| *S. cerevisiae IR-2* | | Continuous | 30 | – | 130 | 99 | 1.8 |
| *S. cerevisiae TISTR 5048* | Sorghum | Batch | 30 | – | Without | 94.12–96.8 | 1.11 |
| *S. cerevisiae NP01* | | Batch | 30 | 4.9 | Without | 99.8 | 2.01 |
| *S. cerevisiae CICC 1308* | | Batch | 37 | 5 | 200 | 93.24 | – |
| *S. cerevisiae*, *Candida brassicae y Z. mobilis* | Beetroot | Batch | 30 | 6.5 | 200 | 72.4–86.1 | 0.53 |
| *S. cerevisiae CHY1011* | Sugar | Continuous | 33 | 5 | – | 87.2 | 1.24 |

Adapted from Zabed et al. (2014)

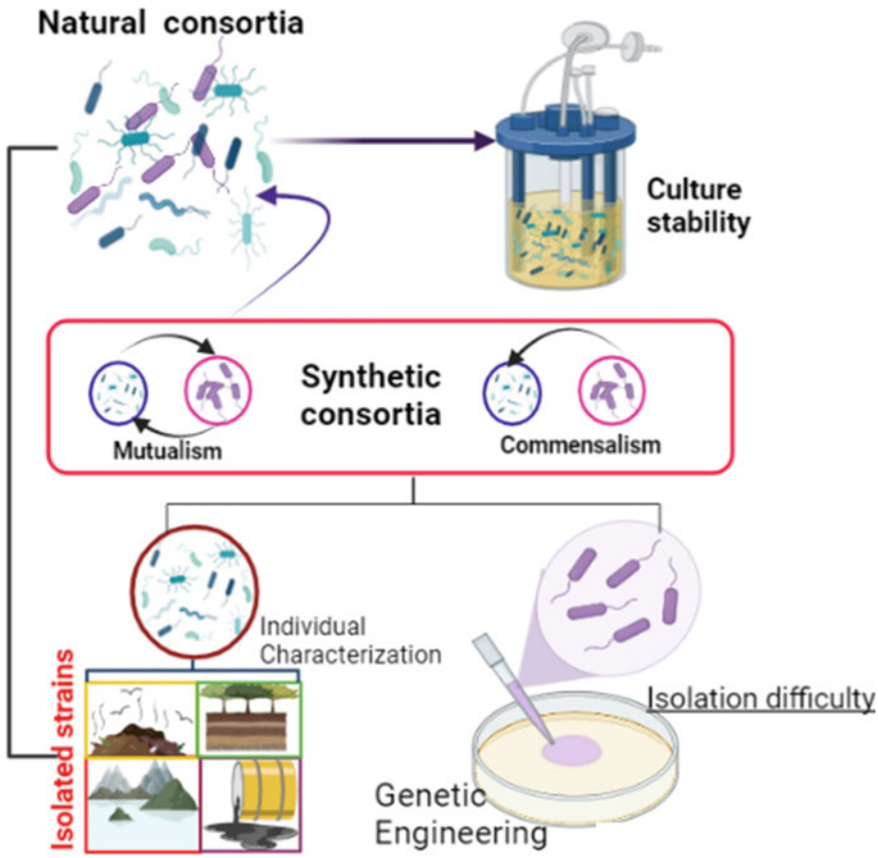


**Fig. 8** Consortia design

Consortia have recently been applied as an innovative and promising strategy in CBPs and biorefineries, and both processes present a link in the circular economy. Classic CBPs are those in which genetic manipulation of a cellulolytic microorganism is carried out to make them ethanologenic or ethanogenic and synthetic consortia which are built through a "bottom-up" approach, that is, enriching two or more strains that were previously isolated, characterized and in some cases genetically modified to coexist in the same environment (Xin et al., 2019). The following two strategies are applied in this regard: (i) microorganisms are used in the same environment that their metabolisms have been analyzed to determine they will not generate competition for the substrate or that the metabolic products of any of the species do not generate inhibition in the other members of the consortium, (ii) genetic modification of several species to induce metabolic synergies. In both cases, the consortia designed require long periods of time, high costs for their generation and maintenance, and they can be constituted of combinations of bacteria, yeasts and fungi to perform complex tasks that are difficult or impossible to achieve by using

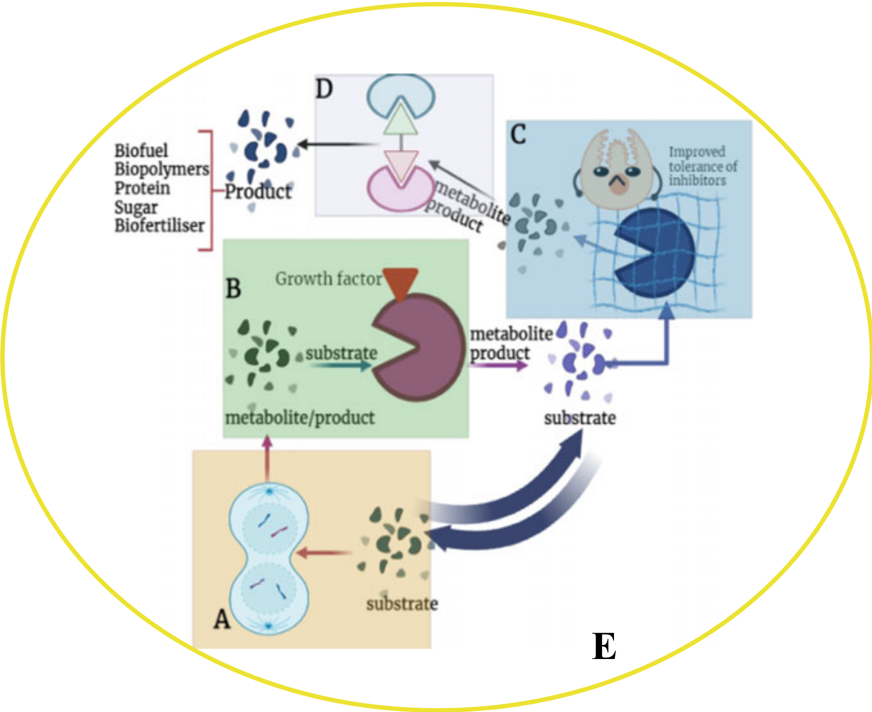


**Fig. 9** Operation of a consortium

a pure strain (Sgobba & Wendisch, 2018). The capacity of hydrolyzing biomass and converting it efficiently into biofuel under sustainable conditions represents a challenge for modern biotechnology due to the following problems: the replication of genes in organisms, the relatively low activity of recombined expressed enzymes (including activity against crude substrates) and the limited tolerance to concentrated by-products such as ethanol (Peng et al., 2018).

On the other hand, there are native consortia with an unknown number of members, originated from environmental communities, including bodies of water (lakes, rivers and seas), soils, effluents, contaminated sites and compost. These consortia are able to adapt to varied and non-constant environmental conditions, such as types and concentrations of substrates, nutrients, in some cases pollutants, temperatures, pH, absence or presence of oxygen, exhibiting attractive characteristics like sophisticated metabolic capacities, robustness to environmental fluctuations promoting stability overtime for other members. For instance, the metabolic synergies carried out by native consortia are biogeochemical cycles (Padmaperuma et al., 2020; Peng et al., 2018). The most widely used strategy for the generation of native consortia is adaptive evolution, which has been widely used to improve a variety of evolved microbial strains with the desired characteristics through the implementation of the rules of natural selection, as presented in the Darwinian theory. This involves a deeper understanding of the metabolic syntrophy of growth coupling, genotypic diversification, phenotypic selection and genotype–phenotype mapping (Mavrommati et al., 2021). Adaptive evolution for consortia consists of collecting a sample of an ecosystem (i.e., rivers, lakes, lagoons, soils, effluents from an industry, contaminated soils and cow manure) (García-Solares et al., 2013; Moreno-García et al., 2021; Reyes-Romero et al., 2021; Valdez-Vazquez & Sanchez, 2018). This sample is the inoculum to enrich the consortium, which may be made up of combinations such as bacteria–bacteria, microalgae–bacteria, microalgae–yeast bacteria–fungus. Under this condition, the inoculum is placed under specific conditions; for example, culture medium, pH, complex substrate, temperature, agitation, then, the species present in that sample will begin to adapt to the new conditions, prevailing the most resistant. The adaptive evolution time is shorter compared to the consortium design performed by genetic engineering. The use of the Winogradsky column has been widely used for the isolation of bacterial strains and microalgae as another adaptive evolution strategy (Hilal et al., 2006). Moreno-García et al. (2021) reported that the microalgae–yeast consortium had an adaptation period of 30 days, adapting in 40 h to Cr (III). Likewise, the cells of the microalgae changed in the presence of Cr (III) as a form of adaptation and evolution to the new environment. García-Solares et al. (2013) indicated that a microbial consortium isolated from a hydrothermal vent with ethene in 15 days adapted to trichloroethylene. Geobacter for electricity generation is another example of native consortia enriched by adaptive evolution (Richter et al., 2008).

The native consortia represent the next generation alternative for fuel production; their use in biorefineries could represent a more profitable process within the circular economy since the nutrients they use can be obtained from almost any ecosystem. They are economical, do not require sterile conditions, controlled pH and temperature, specific care required by a monoculture, avoiding the design of synthetic consortia, and the genetic modification of species, which demand high costs for bioproduct generation, which significantly reduce the sustainability of the process.

Various types of communities have been designed and isolated due to the relevance that consortia have taken in the application of CBPs and biorefineries to obtain biofuels. To this concern, Moreno-García et al. (2021) proposed the use of an isolated consortium in a water treatment plant for the implementation of a biorefinery, which was made up of microalgae–yeasts. The main bioproducts produced were: proteins, lipids and sugars, where this last one was used as raw material for biodiesel and ethanol productions. Xin et al. (2019) conducted a review of CBPs with consortia for the butanol generation; these consortia were made up of bacteria–bacteria, yeast–yeast and even fungi–bacteria, as a proposal to improve the process. Liu et al. (2019a, 2019b) analyzed the isopropanol production from different lignocellulosic biomasses using the EMSD5 consortium, which was designed through CBP, concluding that the application of consortia was a promising strategy for by-product generation. Sadalage et al. (2020) formulated ten synthetic consortia using the combination of three different cellulolytic species of *Bacillus* with *Achromobacter xylosoxidans*, which were evaluated to determine the degradation of grass straw, wheat husk and corn cob. They analyzed the behaviour of the enzymes responsible for hydrolysis during the process, observing that the consortia comprising four bacteria strains were the most promising and active for the degradation of biomass and bioproduct generation. Suastes-Rivas et al. (2020) explored the isolation of a mixed microalgae–yeast culture native from a wastewater plant for biodiesel generation based on fatty acid methyl esters. Raftery and Karim (2017) applied a CBP for large-scale ethanol generation using cane bagasse. Althuri et al. (2017) proposed a CBP for bioethanol yield using a mixture of three different lignocellulosic biomasses, while Xu et al. (2010) studied *Clostridium thermocellum* and lignocellulose material in ethanol CBP.

In summary, the main characteristics of native consortia applied to CBPs and biorefineries to produce biofuels include: (i) the pretreatment of lignocellulosic biomass does not require chemicals decreasing the sustainability of the process, which also increase the costs of the process, (ii) the saccharification and fermentation of the polysaccharides occur in a single reactor simultaneously, ruling out enzymatic hydrolysis, (iii) sterile culture conditions are not required whereby the use of autoclaves is excluded, i.e., reactors of a specific material such as stainless steel, (iv) other bioproducts apart from biofuels can be obtained, (v) output energy doubles the input energy, making this process the most efficient and (vi) a zero waste policy (Sreeharsha & Venkata Mohan, 2021; Valdez-Vazquez & Sanchez, 2018).

The application of native consortia in CBPs and biorefineries underpins the circular economy for biofuel production, like minimizing the emission of greenhouse gases, and removing the needs of landfills, to achieve energy security in a sustainable form. Additionally, novel insights are exchanged with the circular economy model where lignocellulosic materials are completely reintroduced into the business market as raw material for the recovery of economic resources, complying with the four main indicators of the circular economy: sustainable production and consumption, zero waste discharge, systems approach and public awareness. The commercialization and incorporation of biofuels generated from lignocellulosic biomass in the energy market depend on government policies, economists, environmental activists, NGOs and business challenges. Therefore, the circular economy becomes the link between the above points to meet the goals of the 2030 agenda (Awasthi et al., 2020; Sherwood, 2020; Sreeharsha & Venkata Mohan, 2021).

## 5 Summary and Perspectives

The development of native consortia to generate biofuels for CBPs and biorefineries has achieved substantial progress using adaptive evolution, and lignocellulosic biomass as a substrate. These strategies empower the sustainability of biofuel production, positioning themselves as one of the pillars of the circular economy. Although lignocellulosic resources are considered renewable raw materials for these purposes, there are some challenges that have to be addressed, such as the commercialization of native consortia for the industrial production of biofuels, the analysis and description of all the synergies carried out by each consortium (i.e., inventory), the elimination of raw material pretreatments, government, environmental and quality policies for the commercialization and efficient use of various biofuels, and reuse of lignocellulosic biomass. Indeed, this can stimulate that the market for lignocellulosic biomass, native consortia, CBP and biorefineries becomes more profitable in the near future.

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# The Biofuel Industry and Global Trade Nexus

**Deepayan Debnath and Jarrett Whistance**

## 1 Introduction

In recent years, global demand for renewable fuels, driven mainly by country-specific domestic mandates, led to increased biofuels production and trade. To date, ethanol and biodiesel contribute much of the biofuels trade as they are the most established renewable fuels. However, there is potential for the future trade of other renewable fuels as the infrastructure-compatible renewables industry develops. Global biofuels trade accounts for only around one-tenth of all biofuel production. Biofuel trade both in terms of volume and direction depend on many factors, including domestic use mandate policies, tariffs, and crop yields. Figure 1 shows a flowchart diagram from biofuels (ethanol) production to trade.

For decades food crop-based ethanol has been traded and developed into a global market involving large volumes of production, consumption, and trades. In its early stage, the international ethanol trade has tripled from less than 1 billion liters in 2000 to around 3 billion liters in 2007, which further rose to about 9 billion in 2012. In 2021, the world ethanol trade was approximately 10.1 billion liters (Licht, 2022). However, the story is different when it comes to the global biodiesel trade. Biodiesel trade has started more recently and is always driven by policies and incentives that promote biofuels. More specifically, it began in the European Union (E.U.) when many European countries mandated biodiesel blending with diesel fuel. Developing countries, including Argentina and Indonesia, have seen it as an opportunity to export biodiesel to E.U. by converting soybean oil and palm oil into biodiesel. Within a few years, these counties have substantially expanded their biodiesel exports. However, due to stringent environmental regulations, biodiesel exports have declined more recently. In 2012, 21% of the total global biodiesel produced was traded, which is reduced to 14% in 2021 as more countries adopt sustainability criteria on their

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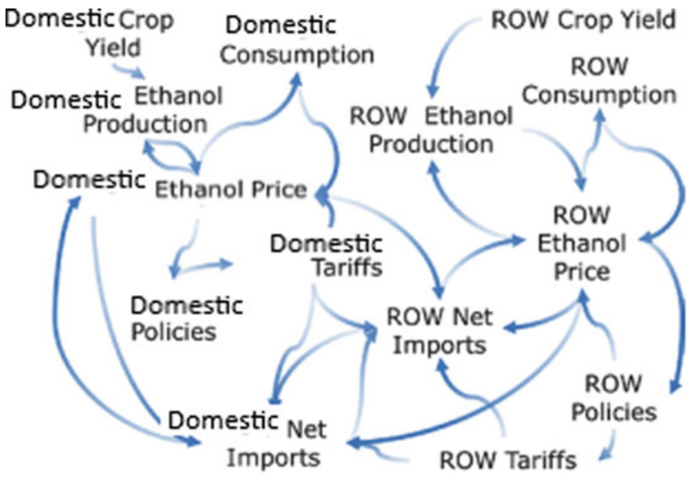


**Fig. 1** Schematic diagram of the biofuels: from production to trade

biodiesel imports (Licht, 2022). Major participants in the liquid biofuels trade are the United States (U.S.), E.U., Brazil, Argentina, and Indonesia.

In the early stage of ethanol trade, the U.S. was the largest importing nation, and Brazil was the primary exporter. However, in recent years, ethanol trade situation has been completely reversed. The U.S. has become the major exporter with the ramping up of maize-based ethanol production technologies. On the other hand, Brazil being the only country with a significant number of flex-fuel vehicles[1] fleet and a domestic ethanol mandate of 27% is demanding more ethanol than they can produce-leading them to be one of the largest importers of ethanol (USDA-FAS, Brazil, 2020).

During the late twentieth century, developed nations including, the U.S. and E.U., have started subsidizing local biofuel production by adopting the domestic biofuels use targets. While the local biofuel industry was nascent, the U.S. has begun importing ethanol to meet its domestic ethanol mandate-driven demand. During the same time, Brazil produced sugarcane-based ethanol at the full production capacity and became a major biofuel-exporting country. Other grains and oilseeds-producing countries in South America have the potential to become the key biofuels exporting countries by producing biofuels at their full capacity. That can be the case for the African countries too. However, biofuels imports among major Asian economies, including China and India, face significant restrictions in the form of high import tariffs. As of 2021, India imposed a 150% tariff on ethanol import for the purpose of blending with petroleum fuels, and biodiesel import is entirely restricted (USDA-FAS, India, 2021). In China, ethanol imports face a 30–70% tariff, and biodiesel tariffs range between 6 and 31% (USDA-FAS, China, 2021). While OECD countries have low tariffs for biofuel imports, importers face stringent environmental regulations among the European nations. In recent years, E.U.'s sustainability criteria have served as a significant

[1] https://afdc.energy.gov/vehicles/flexible_fuel.html.

barrier to the biofuels trade. The import tariffs on agricultural commodities that are used as feedstocks for ethanol and biodiesel production also hinder global biofuels trade. These tariffs on agricultural commodities serve as hidden taxes, raising the cost of domestic biofuels production. Therefore, eliminating such tariffs will reduce biofuels production costs and enhance its efficiency, which may lead to blending more biofuels. More biofuels production may decrease the home country's dependency on imported fossil fuels and positively impact the environment by emitting lower GHGs.

While electrification in the transportation sector is on the rise, biofuels may continue to reduce greenhouse gas (GHG) emissions in the near term. Due to the continued implementation of domestic ethanol and biodiesel mandates, the global trade in biofuels may either stay at its current level or increase in the future—as long as there is fossil fuel use, for example, as in China and E.U. (as shown in Fig. 2a, b).

Domestic biofuels demand may increase for some countries as they adopt higher ethanol and biodiesel mandates, including India and the U.S. (as shown in Fig. 3a, b). The increasing biofuels demand in developing countries will increase agriculture feedstock supply through innovation in the agricultural sector. Biofuels imports are precarious to technologically advanced, less land-intensive countries like Japan that cannot meet their domestic mandate through locally-produced ethanol. Over the last ten years, Japan's ethanol import has increased by 83% (Licht, 2022).

In the future, biofuels production, consumption, and trade should meet the sustainability criteria. Along with other factors, the social aspects of sustainability criteria need to be considered when promoting the production and use of biofuels, particularly in the context of biodiversity and the extinction of certain species of animals. Policy attention should be given to minimize the impact of biofuels industries on the local rural communities where tribal or indigenous people live. Crop-based biofuels require additional land—leading to converting forest and pasture land to cropland—efforts by developing countries to restrict deforestation and forest degradation to promote environmentally sustainable production of biofuels is crucial. On the economic side of the sustainability pillar, biofuels plants should generate additional employment among the rural communities.

In this context, the international organizations, including Organization for Economic Cooperation and Development (OECD) and World Trade Organization (WTO), are crafting and updating the specific guidelines in the form of 'Sustainable Development Goals (SDGs)' to the biofuels producing, consuming, and trading countries to support sustainable development. While WTO is implementing certification schemes for biofuels to be traded based on country of origin, feedstocks used, and sustainability criteria, there is continuing debate on the life cycle analysis used to determine their environmental impact. However, it will always be in question whether certain countries use such criteria as a tool to impose trade restrictions.

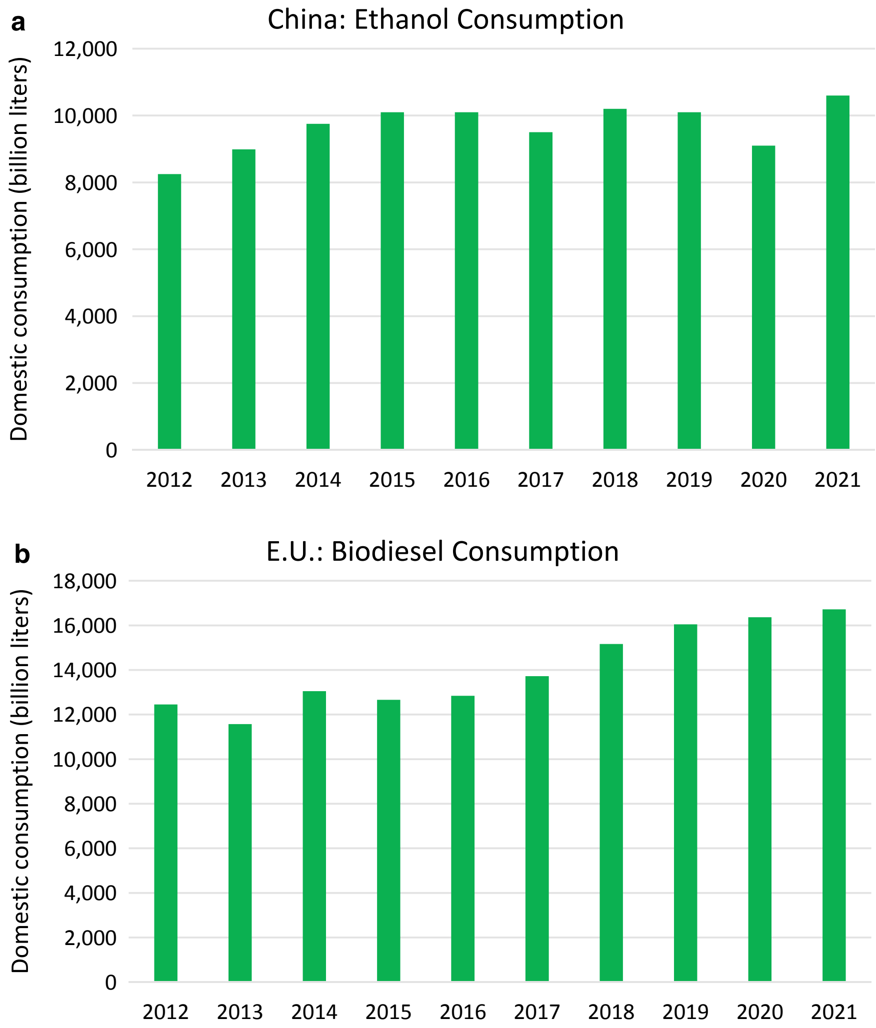


**Fig. 2** **a** Chinese ethanol consumption trend. **b** E.U. biodiesel consumption trends. *Source* Licht (2022)

## 2 Role of Policies in Biofuels Trade

Policies always drive biofuels production, use, and trade. The Biofuels-related policies are categorized into three broader groups. They are as follows:

1. *Promotion of domestic consumption: Strengthening the national energy security*
   - Adopting domestic biofuels use mandates

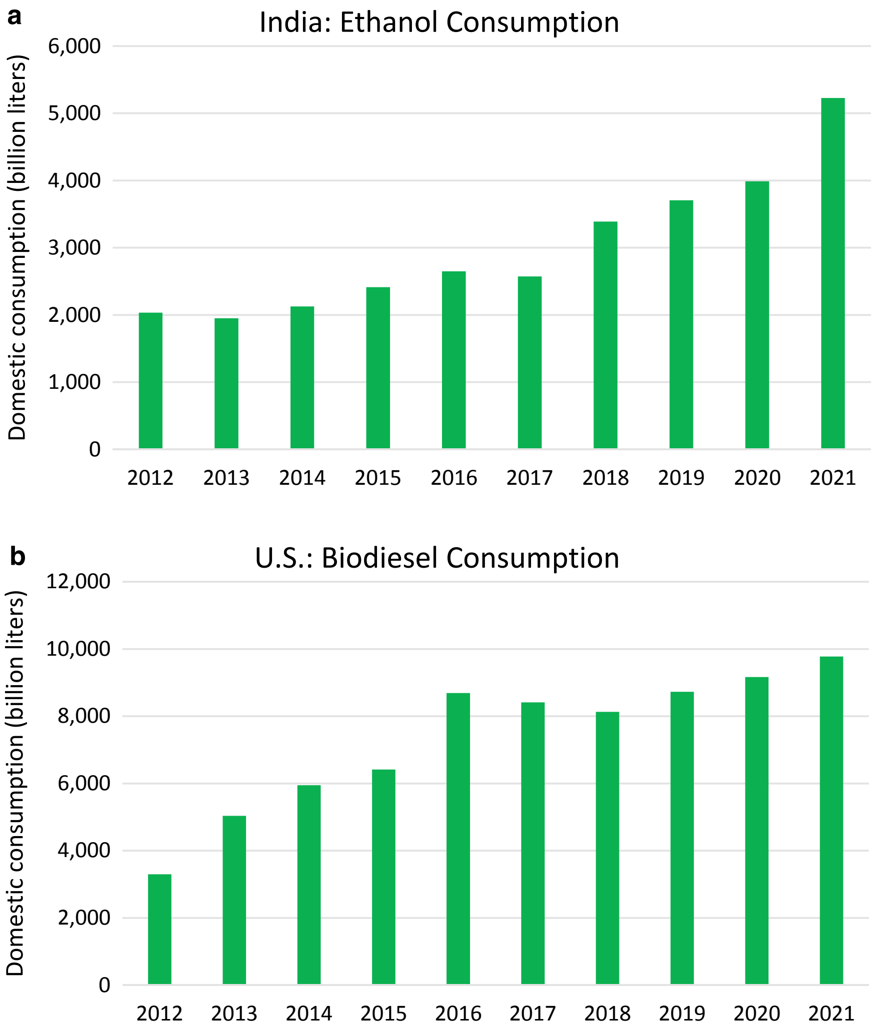


**Fig. 3** **a** India's ethanol consumption trends. **b** U.S. biodiesel consumption trends. *Source* Licht (2022)

- Promoting tax incentives on ethanol and biodiesel production, as well as on tax exemptions for flex-fuel vehicles purchase.

2. *Promotion of domestic production to meet the higher demand*

- Biofuel mandates: Artificially raise price above market conditions
- Support investment though guaranteeing low-interest loans to the biofuel plants
- Investment in research and development

- Tax credits for biofuels facilities
- Various support programs toward agricultural commodities—the key ingredient toward biofuels production.

3. *Trade-related policies*

- Import tariffs
- Non-tariff barriers: Antidumping duties and sustainability criteria
- Export quota.

All these policy instruments have been used to stimulate the production, trade, and biofuels use among the major countries. Some of the most significant policies in effect are the E.U.'s Renewable Energy Directive (RED), the U.S. Renewable Fuel Standard (RFS), and international tariffs: India has implemented import tariffs as high as 150% on ethanol. These policies have greatly influenced the countries' biofuels-related infrastructure growth, which led them to be either an importing or exporting nation. For example, RED in E.U. has caused them to be the major importer of biodiesel, while as the U.S. adopted RFS, they become a net exporter to ethanol from an importing nation.

## 3 Perspective of Biofuels Trade: Past, Present, and Future?

In the early stage of the biofuels boom, many countries heavily used protectionist policies to boost domestic biofuel productions. However, more recently, the focus has been on trading sustainably produced biofuels, which may significantly lower GHG emissions than fossil fuels. While economists emphasized criticizing the negative impacts of trade restrictions and their impact on economic inefficiencies and related costs, little attention was given to answering the questions: (1) What drives biofuels import demand? (2) How does international biofuels trade evolve with meeting the sustainability criteria?

At the beginning of the biofuel era, several countries implemented ambitious mandates mainly driven by two objectives: (1) Becoming self-sufficient in energy. (2) Mitigating GHG emissions. Major countries relied on significantly increasing domestic biofuels production to meet the mandate. Some succeeded, but other less land-intensive countries soon realized that they could not meet the blending mandate by domestically produced biofuels. Their overambitious biofuels blending targets would require them to import a substantial quantity of biofuels, creating opportunities for other countries to produce biofuels to meet the import demand. While the U.S. and Brazil were able to ramp up their ethanol production within a few years, E.U. and Japan quickly realized their impossibility of self-sufficiency. To meet their overambitious mandate, importing biofuels is eminent. Many countries, including Argentina and Indonesia, saw it as an opportunity and started investing in the biofuels industries targeting import markets. However, soon those countries realized that developing biofuels production to support import demands was not viable when the E.U. started imposing biofuel-related trade restrictions—first antidumping duties—next sustainability criteria. For example, Indonesia's biodiesel export declined to 34 thousand MT in 2020 from 1.1 billion MT in 2019 (Licht, 2022).

The fact is that the global biofuels trade remains at about one-tenth of the total world production. In the future, increasing production will not necessarily lead to increasing global biofuels trade. However, like any other commodities, biofuels trade will exist and will depend on the differences between the marginal supply and demand. Feedstocks, mostly grains and vegetable oil prices, contribute to a major portion of the biofuels production prices. Therefore, agricultural price fluctuation significantly impacts biofuels production and trade volumes. The price fluctuations among biofuels, fossil fuels, and feedstocks mainly vegetable oils will be the key factors driving the biofuels trade. Other factors impacting the biofuels trade are:

1. Protection policies on biofuel and feedstock trade.
2. Promotion and subsidies policies related to biofuel and fossil fuel.
3. Blending mandates.

Due to the bulky nature of biofuels that are mostly produced in the U.S. and Brazil has high transportation and insurance costs attached to its trading, which further hinder biofuels trade. While the countries with large biofuels trade volume can significantly influence global biofuels markets, overall, its future is very domed.

Generally, there is always a gain-from-trade. However, that is not the case for biofuels. As in most cases, the blending mandates that the importing countries implement to drive the biofuels trade may distort the market by setting a price above the normal market conditions. However, even in the absence of market distortionary biofuels policies, its export may contradict the importing countries' sustainability goals. In particular, for those countries where cropland is scarce and expanding biofuels production means converting forest and pastureland to cropland. Therefore, the biofuel-producing countries may significantly increase exports by risking sustainability criteria while increasing biofuel production through deforestation. Similarly, if the sustainability among the biofuels producing countries declines, then the sustainability of the bioenergy use among the importing countries will worsen instead of increasing.

In sum, the aggressive mandate increased biofuels production in some countries. However, investing in biofuels productions relying on volatile exports demand may not be viable. In other words, there are no future potentials for large-amount of biofuels exports based on the assumption that the most populated counties in the east and south Asia will significantly increase their biofuels blending mandates. Another negative impact is that it may shift more land toward grain-based feedstock production and increase the risk of hindering the adoption of sustainability toward agricultural production.

# 4 Role of Major Biofuels Producing and Consuming Countries in the Context of Trade

This section of the chapter discusses each county's role in biofuels production, consumption, and trade.

## *4.1 United States*

In the U.S., maize is the primary ethanol feedstock. Maize is processed and fermented into ethanol. 94% of ethanol in the U.S. is derived from Maize (US-DOE, 2020; US-EIA, 2021a). In 2020, the U.S. and Brazil together produced 83% of the total world ethanol (RFA, 2021). However, in Brazil, sugarcane is the major feedstock in ethanol production. In the 2019/20 season, 193 billion metric tons (MT) of maize—around 35% of the total U.S. maize supply—was diverted to ethanol production (USDA-ERS, 2021).

In the U.S., the Energy Independence and Security Act of 2007 (EISA) mandated the use of 'conventional' ethanol mainly derived from maize at 15 billion gallons by 2020 (US-EPA, 2021). Consequently, it ramped up ethanol domestic production and consumption. In the U.S., ethanol is consumed at full capacity on a 10% blending level, the current mandate. In 2020, 10% of U.S. motor fuel consumption was consists of ethanol, and there is ethanol in over 98% of the total U.S. gasoline (US-DOE, 2020; US-EIA, 2021b). For the first time in 2020 since the beginning of the tracking system, the U.S. exported more oil than was imported. On average, in 2020, the U.S. consumed 18.1 million barrels of petroleum products per day (US-EIA, 2021b). Around the same time in the U.S., the number of ethanol refineries and biodiesel plants was 201 and 91, respectively (US-EIA, 2020a, 2020b). The U.S. biodiesel production facilities in 2020 were operated at 72% capacity (US-EIA, 2020b, 2021b). While ethanol blending tax credit of 45-cents per gallon was ended in 2011, the federal administration continually enacts the $1.00 per gallon biodiesel tax credit for producers or blenders of pure biodiesel.[2] The volatile soybean oil (feedstock) and petroleum (energy) prices forced many biodiesel producers to rely on the federal tax credits. The biodiesel tax incentive was recently retroactively reinstated from January 1, 2018, and congress held it in place until the end of 2022 (US-EIA, 2020c).

To encourage the domestic production of ethanol, the American Jobs Creation Act of 2004 imposed a 54-cents per gallon tariff on ethanol imports. However, such import tariffs expired on December 31, 2011. Currently, the tariff on ethanol import is relatively low at 2.5%, and the U.S. imports of ethanol have significantly declined since 2012 (Helmar et al., 2017). The U.S. ethanol imports are currently small (as shown in Fig. 4), and the tariff rate is only 2.5% which suggests that the economic impacts of the current U.S. ethanol tariff have become insignificant.

[2] https://www.transportpolicy.net/standard/us-fuels-biofuel-tax-credits/.

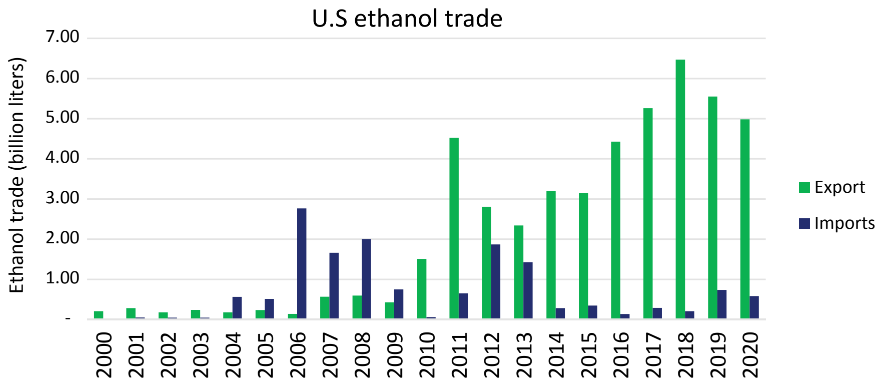


**Fig. 4** Comparison between the U.S. ethanol import and exports. *Source* USDA-ERS (2022)

Historically, the U.S. tariffs on biodiesel have been higher than on ethanol. However, it varies by country of origin. For example, biodiesel imported from Canada has no tariff as they fall under the North American Free Trade Agreement. On the other hand, recently, the U.S. Department of Commerce (DOC) imposed antidumping duties on both Argentina and Indonesia for subsidizing their domestic biodiesel production. Such duties are 50–64% on imports from Argentina and 41–68% on imports from Indonesia. These antidumping duties will give the U.S. domestic producers fair price options and eliminate any incentive that those countries are subsidizing their biodiesel plants to export to the U.S. (Swift, 2017; Thompson, 2017).

From 2014 to 2016, U.S. biodiesel imports from Argentina and Indonesia skyrocketed. According to the National Biodiesel Board, it grew by 464%, resulting in U.S. producers losing a significant portion of the market share (Progressive Farmer, 2020). During the same year, according to the DOC, biodiesel imports from Argentina and Indonesia were estimated to be valued at $1.2 billion and $268 million, respectively. In January 2018, the DOC found that the U.S. biodiesel producers were harmed by unfair trade practices, resulting in the imposition of countervailing and antidumping duty rates ranging from 71.45% to 72.28% and 60.44% to 86.41%, respectively (Progressive Farmer, 2020). However, Argentina's biodiesel exporters were not happy and requested the U.S. officials to renounce those antidumping duties. As of May 25, 2020, after a lengthy review, the U.S. DOC decided to continue to leave those duties in place on Argentine biodiesel imports.

The U.S. DOC determined that Indonesian exporters were shipping their biodiesel products to the U.S. at 92.52–276.65% lower than fair value.[3] This finding was much higher than the previously estimated dumping margin of 50.7%, resulting in the antidumping duties. As of 2017, the antidumping duties were set at 50.71% on palm oil-based Indonesian biodiesel (Walsh, 2017). To reduce the gap between the

[3] https://www.indonesia-investments.com/news/todays-headlines/us-confirms-preliminary-anti-dumping-duty-on-indonesian-biodiesel/item8613.

international and domestic biodiesel prices, the U.S. officials set higher import tariff rates. Such tariffs keep the U.S. biodiesel producers competing against Argentine and Indonesian exporters who receive substantial government subsidies.

Therefore, these constantly evolving trade policies illustrate the importance of understanding the factors that affect the U.S. biofuels trade pattern.

### *4.2 European Union*

During 2009–2010, E.U. contributed to around 65% of the total world biodiesel production (Mark & Hayashi, 2019). E.U. introduced GHG emissions mitigation targets by mandating biodiesel blending. To meet these targets, E.U. heavily subsidized biodiesel production as its original production cost could have been higher than the petroleum product prices at the global market. E.U. consists of many countries. Biofuels are internally consumed and traded, while as a Union, they protect their internal market by stating high import tariffs, resulting in promoting crop-based internal biofuels production. Beyond that, there was a high import tariff on agricultural commodities, to protect biofuels feedstock producers and encourage internal production.

As of August 2021, E.U. retained its import tariffs on U.S. biodiesel for the next five years until 2026, which was originally imposed in 2009. E.U. concluded that removing such tariffs would substantially increase the biodiesel imports from the U.S., which has artificially lowered the prices. According to the European Commission, the U.S. producers were already exporting biodiesel to other countries at a price below their domestic prices—a clear indication that the U.S. was dumping biodiesel to the global market. The commission report also mentioned that the U.S. biodiesel producers were able to lower the local prices as they were benefiting from subsidies, such as tax credits, grants, and loan guarantees. Currently, either E.U.'s antidumping duties on the U.S. biodiesel range from zero to 198.0 euros ($235.36) per ton or duties related to subsidies were from 211.2 to 237.0 euros per ton, whichever is higher.[4]

While E.U. has adopted protectionism with higher import tariffs to protect domestic producers, the Commission set the internal biodiesel blending mandate at a higher level as E.U.'s production is not enough to meet such mandate, leading to biofuels imports. Such strict biofuels blending mandate within E.U. shows their desire to heighten internal energy security and diversify motor fuels mix. In 2010, E.U. introduced—Renewable Energy Directive (RED)—the primary renewable fuels-related policy, including biodiesel. RED sets a 10% renewable energy mandate target for each member state for the transportation sector by 2020. The consequence was dramatic—as it created high demand for cheap soy and palm-oil-based biodiesel —mainly imported from Indonesia and Argentina. Resulting in converting around 4 million hectares of forests land into cropland which led to an estimated 10% reduction of the

[4] https://www.reuters.com/business/energy/eu-extends-tariffs-us-biodiesel-five-years-2021-08-02/.

world's already extinctions orangutan habitations (Exxon Mobil, 2013). Typically, biofuels blending mandate policies target GHG emissions reductions. However, in the case of E.U., ironically, its impact is reverse. Since 2010, within Europe, around 39 million tons[5] of palm and soy-based biodiesel were burned in the transportation sectors, which might emit up to three times more carbon dioxide than the convention diesel that it replaced.

Although, E.U. insisted on diversifying its renewable fuel mix and utilizing energy with higher GHG emissions mitigation. In reality, biodiesel demand within E.U. went up, regardless of the fact that the overall fuel demand shrank due to the pandemic in 2020. This is because countries within E.U. either increased their biofuels blending rate or simply continued to maintain their existing local blending mandate to meet E.U. compliance targets. Around 80% of the crop-based feedstock used to produce biodiesel in E.U. were vegetable oils, mainly rapeseed, palm, and soy. Among them, palm oil reached its highest level, plunging its consumption three-fold, followed by animal fats and soy, which grew by 30% and 17%, respectively, compared to 2019.[5]

In 2018, E.U. adopted REDII—an updated version of RED. Considering the unavoidable deforestation consequences that happened due to the higher volume of palm oil-based biodiesel consumption, the REDII renewable pathway is diverted away from palm oil. According to REDII, biodiesel obtained palm oil use will be constant in 2019 volumetric levels, and thereafter, from 2023 onwards, it will be gradually phased out by 2030. However, it is too late—as palm oil has higher yields and lower prices than other soy, rapeseed, and vegetable oils—it may simply replace those oils. Therefore, intentionally or unintentionally, E.U.'s biofuels policy may drive deforestation, increase GHG emissions, reduce biodiversity, and lead to species extinction.

### *4.3 Brazil*

Brazil is one of the largest bioethanol consumers. At the same time, they are one of the most efficient and low-cost sugarcane-based ethanol producers. Today, Brazil has the highest fleet of vehicles globally with a combustion engine that runs either on bioethanol or fossil-based fuels—commonly known as 'Flex-fuel Vehicles'. There were around seventy-five million such cars, 73% of the total Brazilian vehicles fleet.[6] The rate at which such a rapid transition happened was extraordinary. Within only six years, when in 1975 the Brazilian government adopted 'Proálcool'—National Alcohol Program, almost 90% of the new vehicles sold could drive on ethanol.[6] However, as during the 1990s, when the crude oil price dropped, consumers turned away from ethanol-based vehicles https://www.rapidtransition.org/stories/the-rise-of-brazils-sugarcane-cars. The Brazilian government promptly responded, and from the early 2000s, started actively promoting the 'Flex-fuel Vehicles'. By 2004, almost

[5] https://www.transportenvironment.org/discover/10-years-of-eus-failed-biofuels-policy-has-wiped-out-forests-the-size-of-the-netherlands-study/39.

all new cars in the Brazilian market were ‘Flex-fuel Vehicles’ (FFV). The FFVs had proven to be incredibly popular among Brazilians.

This is how the Brazilian government was succeeded in establishing a greener, cheaper, and more reliable alternative renewable fuel for its fleet of vehicles. Before 1975, before ‘Proálcool’ was established, 80% of Brazil’s domestic fuel demand was met by imported oil. However, things were changed drastically once ‘Proálcool’ was adopted, and by 2009, ethanol made over 60% of their total motor fuel consumptions.[6] Over 1975–2000, the entire ‘Proálcool’ program cost the Brazilian government around $30 billion. However, Brazil saved over $15 billion annually by not importing crude oil.[6] This phenomenal program resulted in ethanol being much cheaper than gasoline in Brazil. In 2008, ethanol price was nearly half the price of gasoline.

Traditionally, Brazil was a net ethanol exporter to the world market. Until recently, Brazil exempted up to 750 million liters of ethanol from import tariffs. However, with increasing domestic ethanol demand by the FFV owners, the local sugarcane-based biorefineries could not keep up with that pace. It resulted in Brazil importing a significant volume of ethanol, mainly from the U.S. In 2018, Brazil imported 1.8 billion liters of ethanol, around 119% more than the previous year (Licht, 2022). A sudden increase in ethanol imports triggered the Brazilian government to slap a 20% tariff on U.S. ethanol imports (Doran, 2020).

Ethanol derived from sugarcane in Brazil is considered sustainable renewable fuel, with up to 90% less direct emissions than fossil fuels. However, the story is entirely different when indirect emissions due to deforestation are considered. Therefore, the broader question remains whether crop-based biofuels are sustainable.

### 4.4 Argentina

Argentina’s biodiesel industry mainly developed relying on soy oil as a feedstock, but it differs in its trade orientation in contrast to Brazil. Unlike Brazil, Argentinean biodiesel producers primarily focus on capturing a significant portion of the global biodiesel export market. Favorable biofuels policies, such as tax credits for biodiesel production and much lower biodiesel export taxes than soy oil exports, further incentivize Argentine biodiesel export (Lamers et al., 2011). Another factor that might lead to the substantial increase in Argentinean biodiesel exports was the biofuels use mandate in E.U. and the U.S. They resulted in the development of the biodiesel industry, which focused primarily on exporting it to the E.U. and later to the U.S. Argentina has also implemented specific policies that encourage a gradual increase in domestic biodiesel consumption through blending mandates. As of 2015, the Argentinean domestic mandate remains at 10%, and the current average blending ratio was at 8.4% (USDA-FAS, Argentina, 2016). However, the domestic production

[6] https://www.rapidtransition.org/stories/the-rise-of-brazils-sugarcane-cars/.

volumes were simply surpassing the consumption and maybe continue in a similar fashion, letting Argentinean biodiesel plants focus on exports (Lamers et al., 2011).

Argentina has become a net fossil fuel importer during the past decade, and diesel accounts for roughly two-thirds of its motor fuel use (USDA-FAS, Argentina, 2016). At the same time, Argentina has become one of the World's largest soy oil producers and exporters. Given these facts, along with sophisticated soybean and soy oil supply chains—the Argentinian government started promoting biodiesel production for domestic use and export—to reduce the foreign burden of fossil fuel imports and support domestic agribusiness. Following Brazil's biofuels program's success, the initial intent of the Argentine biofuels programs was to provide support to small- and medium-scale biofuel-feedstock farmers. But soon, the large-scale and highly efficient soy industry took charge and became the primary supplier of the vegetable oil-based feedstock to the domestic biodiesel industry.

There was a significant major difference between Argentina and Brazil's biodiesel market development. Argentina's biodiesel market mainly revolved around export opportunities, while Brazilian ethanol producers focused on meeting the mandate-driven domestic demand. Argentina started exporting a significant share of its production. By 2014, almost 70% of the total domestically produced biodiesel was exported (USDA-FAS, Argentina, 2016). There were two factors that have enabled the biodiesel industry to be export-oriented. First, the Argentinean administration intentionally kept the export tax on biodiesel substantially below duties on soybeans, soy meal, and soy oil; and secondly, the introduction of renewable fuel target policies in the U.S. and E.U.

As noted in earlier sections, during the mid-to-late-2000s, E.U.—a major consumer of diesel fuels—introduced renewable energy blending targets. During the same time, the U.S. introduced the RFS, which mandated domestic biodiesel use beyond the production capacity. These biofuels blending mandate policies in foreign countries led to an export opportunity to the global biodiesel market, and Argentina grabbed that opportunity. Soon, they became a competitive supplier of biodiesel to those markets. However, in 2013, the E.U. imposed antidumping duties on Argentinian biodiesel (USDA-FAS, Argentina, 2016). Fortunately, Argentina had become a major biodiesel exporting hub by that time. They started competitively exporting it to the African continent, where biodiesel was used in discretionary blending as it was price competitive with diesel fuels. However, during recent years, biodiesel export decreased from 1.65 million MT in 2017 to 540 thousand MT in 2020 (Licht, 2022). There were two major contributors: (1) Imposition of antidumping duties on Argentinean biodiesel by both the U.S. and E.U. and (2) COVID-19 that lowered overall fossil fuel consumption. The future of Argentina's biodiesel export market remains uncertain.

While the export demand has driven Argentina's biodiesel industry, its future remains uncertain. However, how it will respond to stricter global environmental policies over cleaner energy and meet the sustainable criteria over the next few years is much less clear. Considering the vital role that the vegetable oil sector plays in the Argentinean economy, it is likely that the biodiesel sector will continue to be promoted. However, more robust sustainability criteria in domestic biodiesel production maybe required to maintain their export share.

### 4.5 Indonesia

Intending to reduce foreign dependency on fossil fuels and support the local palm oil sector, the Indonesian government introduced the domestic biofuels mandates in 2006. Initially, it was set at 5% of the total transportation fuel consumption by 2025 (Caroko et al., 2011). Over time, as the market conditions changed, the government ramped the biodiesel mandate target to 30% by 2020. However, in reality, Indonesian renewable energy targets has never been achieved, and by 2015 only 17% of the total biodiesel plants capacity was utilized (USDA-FAS, Indonesia, 2016).

Three major factors that motivated the administration for this ambitious biodiesel mandate policies are:

1. Persistently increasing crude oil prices through mid-2014
2. Indonesia's overall growth in the transport sector, more specifically, the growth in diesel fuel demand
3. Large and growing palm oil sector.

With the increasing population and income, Indonesia's overall transport sector was expected to grow by 3.7% per annum through 2020 (OPEC, 2014). Meanwhile, Indonesia became the world's largest producer of crude palm oil (CPO), surpassing Malaysia. Driven by high palm oil yields, low land and labor costs, Indonesia became the top exporter of CPO in 2008. There was an export tax on the Indonesian CPO export, which generated significant revenue. A portion of that revenue supported domestic biodiesel production, resulting in Indonesia becoming a major biodiesel exporter. However, the biodiesel exporter faced many hurdles as such: (1) Due to low crude oil prices, discretionary blending demand for biodiesel in the international market declined, and (2) adoption of major environmental criteria on biodiesel import by the U.S. and E.U.—almost immediately disqualified Indonesia from exporting biodiesel to those markets. Between 2013 and 2020, Indonesia's biodiesel exports dropped from 1.7 to 0.03 million MT. Meanwhile, during the same time, domestic biodiesel production and consumption increased from 2.4 to 7.8 million MT, and from 0.74 to 7.3 million MT, respectively (Licht, 2022).

Despite Indonesia's administrations' strong support toward domestic biodiesel production, the expansion of land to grow oil palm to meet the increasing feedstock demand was heavily criticized by the international communities. The oil palm-driven land expansion might result in substantial social costs related to environmental damages due to deforestation and forest fires on high carbon soils (Barreiro et al., 2016; World Bank, 2016). While there were huge environmental damage costs due to those fires, at the same time, the biodiesel-related oil palm feedstock sector generated significant social benefits as well (World Bank, 2016). Studies have shown that there were rising incomes, improved nutrition, and reduced poverty in the regions where the palm oil sector expanded within Indonesia (Edwards, 2016; Euler et al., 2017). However, those social benefits happened at the costs of environmental damages, as in these regions, there was the expansion of the land area to increase oil palm production.

Despite these facts—based on current Indonesia's biodiesel production, consumption, and export trends—it appears that the government support toward biodiesel industries will continue to protect palm oil interests and promote rural development. While Indonesia may lose a significant portion of the international biodiesel export market due to stricter environmental regulations, current policies will lead to steady growth in mandate-driven domestic consumption.

## 5 Conclusions

Originally policymakers envisioned achieving three important goals through biofuels blending mandates: (1) Energy independence, (2) Reducing GHG emissions, and (3) Rural development. However, none of them were fully achieved.

Historically, there was rapid growth in the biofuels sector, mainly ethanol production, consumption, and trade spearheaded by the U.S. and Brazil. E.U. also joined the race by mandating domestic biodiesel use and started importing a significant portion of it from Asian and South American countries. The countries that implemented stricter domestic mandates ended up importing biofuels, while scientists have proved that crop-based biofuels led to more emissions than conventional fossil fuels. Biofuel policy-driven rural development did occur. However, it only happened when small-scale producers produced biofuels. Contrarily, the production costs of such biofuels were relatively high, as those producers faced challenges with the economics of scale and their contribution to national energy security and GHG emissions reduction were modest. Unfortunately, biofuels-related rural development took place at the costs of environmental damages linked with deforestation and forest fires.

Unlike other commodities, policies drive biofuels trade either its ethanol and biodiesel blending mandate or higher export tax on vegetable oil and import tariff on biofuels. In the future, environmental concerns related to crop-based biofuels and the adoption of climate change mitigation policies will dictate the biofuel trade, production, and consumption. Within the last couple of years, the overall global import of biodiesel has fallen substantially due to the adoption of environmental regulations by the importing countries. The market also plays a critical role in the biofuels trade—when the biofuels price is lower than crude oil—the formers' demand spikes and vice-versa.

However, the recent trends are less optimistic for the biofuels market, particularly for the exporting nations. The mandate-driven biofuels demand is expected to grow at a much less faster rate. Thus, countries promoting biodiesel export need to revise their biofuel policies to anticipate significantly lower export demand. In any case, it will be better for any country to develop their country-specific biofuels strategy considering their long-term climate mitigation goals and the local producers' need.

Another critical factor necessary for the future biofuels trade is the sustainability criteria. Establishing international sustainability standards may be helpful to discourage unsustainable production practices, mainly deforestation and forest fire driven growth in biofuels feedstocks production. However, importing countries may not use them as a tool to restrict the biofuels trade.

Therefore, it can be predicted that the price volatility, political environment, and government priorities will create tension and uncertainty toward the future of biofuels over the following decades.

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