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The Sustainability of Biodiesel Synthesis from Different Feedstocks: A Review

Katlego Bombo [1], Tumeletso Lekgoba [1], Oluwatosin Azeez [1,2] and Edison Muzenda [1,3]*

[1] *Department of Chemical, Materials and Metallurgical Engineering, Botswana International University of Science and Technology, Palapye, Botswana*
[2] *Department of Chemical Engineering, Federal University of Technology, Minna, Nigeria*
[3] *Department of Chemical Engineering Technology, Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg, South Africa*

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Abstract

Currently, the world is facing an energy crisis due to an increase in the global energy demand and this has led to an increased dependence on fossil fuels for energy generation and transportation. The steady rise in the world population which is more than seven billion currently is met with an increase in fossil fuel consumption thereby increasing the threat of fossil depletion and an apparent energy deficit. Fossil fuel emissions pose a threat to the environment and the general human population due to risks posed by greenhouse gases they produce. Biodiesel is recognized as a suitable alternative to fossil fuels due to its biodegradable, renewable and environmentally friendly nature. Biodiesel sources are classified into first, second and third generation based on their origin and type of feedstocks used. There are fourth-generation feedstocks which are biologically man-made resources that are currently at the embryotic stage of research. This paper reviews the sustainability of using Jatropha curcas seeds and microalgae for the production of biodiesel. It highlights an evaluation of the oil yield, composition and performance of the biodiesel derived from both sources whilst assessing the viability of individual feedstocks in biodiesel production. Additionally, different methods of biodiesel production are also assessed.

Keywords*: Biofuel; Jatropha curcas; Microalgae; Transesterification; Triglycerides.*

1. Introduction

Today, modern lives have come to depend on energy for its profusion, convenience and potential with fossil fuel energy largely contributing to the worldwide energy consumption. With factors such as the increase in world population and rapid industrialization, the global energy demand has also increased [1]. Therefore, increased demands for fossil fuels has led to the depletion of fossil fuel reserves [2]. The continuous use of fossil fuels mainly in transportation, electricity and thermal energy generation has largely contributed to the anthropogenic greenhouse gas (GHG) emissions. These emissions pose the threat of global climate change due to global warming [3]. Whilst GHGs largely contribute to global warming and climate change, GHGs and harmful matter released from the transportation industries pose a threat to human life and the environment in general [4]. In order to explore more sustainable means of meeting the global energy demand, biofuels have been explored in past decades as practical alternative sources to fossil fuels and this has opened the doors to explore the different biofuel sources and the feasibility of the fuels produced. Biofuels are liquid or gaseous fuels that are made from biomass feedstock and these feedstocks are biological resources from edible crops, non-edible crops, animal fats, wastes and microbes. The types of biofuel include, biodiesel, bio-methanol, biogas, bioethanol and bio-dimethyl-ether [5]. Biodiesel, which is the main diesel fuel alternative in the EU is mainly produced from oils derived from the aforementioned feedstocks [4]. Unlike fossil fuels, biofuels are biodegradable, renewable, relatively clean and environmentally safe fuels derived from biological sources such as plants, animals and microbes [7]. Furthermore, biodiesel is sulphur free, it is a better lubricant and the use of biodiesel has great socio-economic benefits [8-9]. The versatility in biodiesel is also owed to the fact that different feedstocks can be used in its production. In a sense, biodiesel has better properties than those of petroleum diesel. Therefore, the use of biodiesel has become more attractive due to these reasons and its potential to reduce the carcinogens released into the environment [2]. However, drawbacks typical of biodiesel in contrast to petroleum diesel fuel include higher viscosity, lower volatility, higher pour point and cloud point, lower energy content and slightly higher nitrogen oxide emissions [10]. Other than making engine modifications, researchers have worked to address the above mentioned problems by changing the feedstocks used, modifying and exploring different biodiesel production processes [1]. In the pursuit for sustainable energy sources that will not only meet the global energy demand but also have minimal environmental impacts, key factors such as environmental, socio-economic and operational parameters must be considered. This review highlights the different generations of biodiesel feedstocks. It includes an analysis of the different production processes and methods adopted to increase biodiesel yield and obtain a more refined product.

2. Generations of biodiesel

Despite the recent technological advancements with the electric car through converting solar energy to electricity, biodiesel is still of great importance mainly in the transport sector. While biodiesel can be used independently to fuel automobiles, it can also be mixed with petroleum diesel as it has similar properties and has lower exhaust emissions [1]. As previously stated, biodiesel is a biofuel produced from the oils derived from edible crops, non-edible crops, waste, animal fat and algae. The transesterification of oils derived from these feedstocks form mono-alkyl esters of long chain fatty acids, otherwise known as biodiesel [2]. It can be classified into first, second and third generation biodiesels based on the origin of the feedstocks.

2.1. First generation biodiesel

Biodiesel that can be derived from edible feedstocks such as sunflower, palm, rapeseed, soybean, coconut, mustard and olive oil, are considered as first-generation biodiesel feed stocks [11]. Edible oilseed crops were popular at the beginning of the biofuel era hence their classification as first-generation biodiesel feedstocks. The limitations on the use of these feedstocks include the risk of reducing the food supply, high costs and failure to adapt to various environmental conditions [12]. According to Balat [13], between 2004 and 2007, the global use of edible oils for biodiesel production increased to 34%, that is, the use of edible sources of biodiesel increased faster than its production and it was projected to further increase by the years. Therefore, this has led to the concern of risked food supply due to competition with biodiesel feedstocks and this constraint heralded the shift to other sources for biodiesel production.

2.2. Second generation biodiesel

Another source of biodiesel, the non-edible oils are classified as second-generation biodiesel sources and examples of these include Jatropha oil, Nagchampa oil, Rubber seed oil [14]. As mentioned earlier, the limitations of using first generation feedstocks redirected researchers to investigate non-edible feedstocks as biodiesel sources. Unlike edible feedstocks, non-edible feedstocks present no competition with food supply meaning they can also grow in unproductive land since they are well adapted and can grow under extreme conditions with low fertility and moisture [15]. The *Jatropha curcas* plant for example, is drought resistant and can grow in rocky-strewn terrains, soils with little or no agricultural value, in the deserts and saline soils [16]. The production of these non-edible crops can also present the opportunity of employment for small scale farmers through the cultivation of these crops in rural areas.

According to Dufey [6], sugarcane farms (utilized in bioethanol production) largely employ unskilled labour and poor workers in rural areas in Brazil, creating more jobs than the fossil fuel industry. Therefore, the utilization of large unproductive lands in rural areas coupled with poverty alleviation programs for small scale farmers in the cultivation of biodiesel crops can boost the rural agricultural sector. Moreover, since they can grow in unproductive and unimportant lands, they thus require less use of farming lands in order to grow, preventing a competition for land with edible crops. Even though this generation of biodiesel prevent competition with food production down the line, they have disadvantages of requiring more alcohol for transesterification and usually come out to be more viscous. Therefore, other alternative biodiesel sources are considered which could be more accessible and feasible [17]. Such alternatives are discussed in the next section.

2.3. Third generation biodiesel

Algae, waste oils (fish oil, cooking oil etc.) and animal fat are classified as third generation feedstocks, hence, biodiesel originating from these oils is classified as third generation biodiesel. The major advantages of using these sources include; high lipid concentrations, reduction of GHG emissions and their high growth and production rate [18]. Biodiesel sources of the third generation are versatile, economical, and readily available and do not have an impact on the food supply, hence they resolve most of the issues arising from the utilization of the previous biodiesel generations [4]. Even though the use of waste oils and animal fat can diminish water pollution and the amount of waste handled, the quantity of animal fat and waste that are presently available are insufficient to meet the global demand for biodiesel. Algae is currently regarded as the latest inexhaustible source of biodiesel among the non-edible oil sources and is projected to surpass palm oil, which accounts for 31% of the global biodiesel output lately. Where palm oil produces about 70% by weight of dry biomass, microalgae has the potential to produce a 25-fold higher oil yield by weight of dry biomass due to their extremely fast growth and higher oil content [19]. Feedstocks for various generations are shown in Table 1.

Table 1. Some biodiesel sources for the different generations, adapted from [1]

1st generation	2nd generation	3rd generation	4th generation
Cashewnut	*Aleutites fordii*	Animal tallow	Photobiological solar biodiesel
Coconut	Babassu tree	Biomass pyrolysis	Electrobiofuels
Corn	*Calophyllum inophyllum*	*Botryococcus braunii*	Synthetic cell
Cotton seed	*Castor*	Chicken fat	
Hazelnut	*Cerbera odollam*	*Chlorella vulgaris* algae	
Mustard	*Crambe abyssinica*	*Dunaliella salina* algae	
Olive	*Jatropha curcus*	Poultry fat	
Palm	*Jojoba*	Fish	
Pistachio	*Karanja*	Waste cooking oil	
Raddish	*Mahua indica*		
Rapeseed	Milk bush		
Rice bran	Nagchampa		
Soyabean	Neem		
Sunflower	Nicotiana tabacum		
Tigernut	Petroleum nut		
Walnut	Rubber seed		

From the information gathered about the different generations of biodiesel, it is quite clear that biodiesel can be attained from different sources. The biodiesel obtained from these various sources also have varying degrees of purity due to the differences in the chemical makeup of the sources and the synthesis method. According to Singh and Singh [2], the most important step for biodiesel synthesis is the feedstock selection. Feedstock selection heavily relies on several factors like, the climate, the economic aspect of the country i.e. viability of the feedstock in alignment with the economy. The composition, oil yield and the availability of the feedstock are also among the factors to consider. Table 2 shows the varying oil yields from different feedstocks. It should also be noted that the use of edible feedstocks heavily affects the food supply chain and in countries where food security is relatively low, edible oils are the least attractive choice [1].

Table 2. Oil yield of different biodiesel feedstocks, adapted from [4]

Base material	Lipid content (% in biomass dry weight)	Oil yield (L/ha/year)	Land used (m^2/year/kg bio-diesel)	Biodiesel productivity (kg biodiesel/ha/year)
Soybeans	18	636	18	562
Rapeseed	41	974	12	862
Sunflower	40	1070	11	946
Palm oil	36	5366	2	4747
Castor	48	1307	9	1156
Microalgae	70	136,900	0.1	121,104

3. Alternative biodiesel feedstocks

3.1. *Jatropha curcas* oil

Jatropha curcas, L. is a hardy multipurpose shrub that belongs to the multispecies Euphorbiaceace family. While indigenous to the Caribbean and different states of America, it also grows wildly in arid and semi-arid tropical regions, including Africa and Asia [20]. According to a study by Thapa *et al*. [21], the physical and chemical properties of *Jatropha curcas* oil showed more adherence when compared to other biodiesel feedstocks and proved to be suitable for biodiesel production. With an oil content of approximately 20-60%, *Jatropha curcas* seed oils have a higher oil content than that of other oil plants including palm oil (44.6%) which around the year 2017, accounted for much of the global biodiesel output [22]. According to Akbar *et al*. [23], *Jatropha curcas* oil has a high percentage of free fatty acids (FFAs), ranging between 1.68 and 2.23% whereas oleic acid was used as a factor of measurement for suitability as feedstock. By standard, a % FFA content >1% w/w results in saponification during transesterification which reduces biodiesel yield and causes difficulties in downstream purification and separation processes [23]. *Jatropha curcas* is seen to be disadvantageous in this aspect since its FFA is greater than unity and for this reason, two steps transesterification is normally required to reduce the FFA content when it is used as feedstock for biodiesel production. According to Gunstone, vegetables oils should constitute highly of monounsaturated fatty acid, that is, have a low saturation in order to fit diesel alternative criterion. This is mainly characterized by palmitic (14.2%), oleic (44.7%) and linoleic acid (32.8%) [25]. Jatropha curcas oil which evidently contains some level of monounsaturated fatty acids is a suitable substitute for the production of biodiesel.

According to Jain [26], Jatropha produces 4 – 6 MT of seeds per hectare per annum in relatively poor soils, where one hectare of plantation yields 1.6 MT oil. This yield however would vary according to the climatic conditions of the area and the agricultural methods practiced. While Jatropha Curcas seems like a promising plant in biodiesel production, recent studies have shown that large scale production may not be economically viable. According to Kgathi *et al*. [27], studies have shown that low yields from Jatropha cultivation has led to difficulties in achieving economic sustainability in sub-Saharan Africa. A scoping study by Locke and Henley [28] in some African countries indicated that Jatropha cultivation projects only manages to use between 0.65 % and 3.60%,of planned land areas . Moreover, Rapier [29] observed that Jatropha Curcas has a low seed yield of 0.5T/hectare. Despite this, Jatropha curcas has been recognised as one of the most important sources of biodiesel in some countries of which India is an example.

3.2. Karanja oil

The Karanja plant, known as Pongamia pinnata (*P.pinnata*) is a leguminous tree native to the Indian subcontinent and several countries in South-east Asia. This medium sized tree does well in humid and subtropical regions and has therefore been successfully integrated in other parts of the world including Australia, China, the US and New Zealand [30]. The Karanja seed have a varied oil content of 25-40 wt. %, with Ahmad *et al*. [31] quoting an oil seed content at approximately 35% by weight. While the fast growth properties of the *P.pinnata* and its ability to grow in marginal lands make it a sustainable alternative biodiesel source, the plant can only show its full growth and productive potential in regions where annual rainfall ranges between 500-2500 mm, [32]. According to Balat [13], *P.pinnata* is predominantly characterized by fatty acids, oleic acid (51.8%), followed by linoleic acid (17.7%), palmitic acid (10.2%) and stearic acid (7.0%). The fatty acid compositions cited above, are within ranges (44.5–71.3%), (10.8–18.3%) and (2.4–8.9%) as quoted by Singh *et al*. [1] for oleic, linoleic and stearic acid respectively. According to Sharma *et al*. [33], *P. pinnata* oil which has a high %FFA requires a two-step transesterification process just like Jatropha oil, where the first step involves esterification of the oil to remove the FFAs and the second step is the alkaline catalyzed transesterification of the oil to methyl esters.

An investigation by Raheman and Phadatare [34] found that the kinematic viscosity of Karanja oil is significantly higher than that of diesel, up to 10.7 times higher. A higher viscosity as quoted by Balat [13] affects the smooth flow of diesel in the engine and is a cause of some engine problems that are associated with biodiesel. However, Raheman and Phadatare [34] further discovered that esterification of karanja oil into karanja methyl ester reduced the viscosity by a factor of 2.9 from that of the oil. The study also went on to iterate the significant reduction of the kinematic viscosity to acceptable standards by blending varying proportions of karanja biodiesel with petroleum diesel. Hence it is conclusive that Karanja methyl ester and diesel blends could be promising diesel substitutes. Karanja oil may be a promising biodiesel feedstock; however, limitations are posed by the growth conditions of the leguminous tree which make it unsustainable for arid and semi-arid climatic conditions.

3.3. Microalgae

Microalgae are eukaryotic or prokaryotic microbes that either have a unicellular or multicellular structure. They are photosynthetic microorganisms that contribute to about 50% of the world's photosynthetic activity [35]. Microalgae can be cultured using light energy and carbon dioxide via photosynthesis in shallow waterbodies. With that said, they are an aquatic species that cultivates in different natural waters including brackish water, fresh water, marine and saline conditions. Some examples of the microalgae found within these environments and used in commercial applications today include *Dunaliella salina*, *Chlorella vulgaris* and *Botryococcus braunii* [36]. Because of their unicellular and multicellular cell structures, they can survive in harsh conditions i.e. waters with high salinity [37].

Microalgae can reproduce their own biomass within a day, they can also achieve a complete growth cycle within a couple of days and are considered 10-20 times more competitive than traditional biofuel crops such as soybean and palm oil. While the lipid content in the microalgae dry biomass unit may vary for different species, the volumetric productivity of the species must also be considered in order to assess the feasibility and select the best microalgae to produce biofuels [4]. According to Balat [13], algal oil which mainly constitutes saturated and monounsaturated fatty acids has considerably optimal proportions of fatty acids. Data by Mata *et al*. [4], also indicates that microalgae are superior in lipid content, oil yield and biodiesel productivity in contrast to traditional edible feedstocks. Microalgae also promises to be a sustainable feedstock since it uses up an almost insignificant amount of land as opposed to plant based feedstocks. However, while microalgae promises to be a more advanced diesel substitute, challenges in efficient cultivation and harvesting techniques make the initial upstream processes in biodiesel production difficult and expensive. In consonance with this, Li *et al*. [38] suggested that drying harvested algae biomass would be a costly and energy consuming process due to a high water content of biomass and inadequacy of the harvesting process in water extraction.

3.4. Waste cooking oil (WCO)

Waste cooking oil from its name is oil waste derived from food industries, households and restaurants, having been used for the sole purpose of cooking. Waste cooking oil generated per country varies and is largely dependent on the consumption of vegetable oils. According to Knothe and Steidley [39], utilizing waste cooking oil in biodiesel production takes a step further into curbing environmental pollution associated with WCO disposal and a lot of the challenges faced during disposal. The low cost and easy availability of WCO also makes it an economically sustainable choice for biodiesel production [40].

In biodiesel production, waste cooking oils are classified according to their FFA content, that is, WCO with less than15% FFAs are called yellow grease and brown grease for greater than 15wt% FFA's [40]. While biodiesel properties from waste oils may differ due to the use of different vegetable oils and other factors such as exposure to different temperatures and differences in cooking and oil storage times. Studies quoted by Knothe and Steidley [39] show that there have been no significant difference between undistilled biodiesel from traditional vegetable oils and biodiesel sourced from their respective waste oils. However, due to their high FFA content and contamination with other compounds from frying, this creates huge problems during biodiesel production. For this reason, Kulkarni and Dalai [40] suggested that the enzyme catalyzed transesterification could be the better option for biodiesel production from WCO. Kulkarni and Dalai [40] rules out the two-step transesterification process due to its lack of economic feasibility as many steps are involved which could be rather costly. On the other hand, Wang *et al*. [41] points out the base catalyzed transesterification for refined WCO with an FFA content less than 0.5wt%. Acid catalyzed transesterification with excess methanol and high pressure is also prescribed for WCO with >10 wt. % FFA.

4. Conclusion

Despite the recent technological advancements with the electrical car through converting solar energy to electricity, biodiesel is still of great importance mainly in the transport sector. Biodiesel is a biofuel produced from the oils derived from edible crops, non-edible crops, waste, animal fat and algae. From the information gathered about the different generations of biodiesel, it is quite clear that biodiesel can be attained from different sources. The biodiesel obtained from these various sources also have varying degrees of purity due to the differences in the chemical makeup of the sources. This review covered the three generations of biodiesel where each generation had its advantaged and disadvantages. Also highlighted were the alternative biodiesel sources, with the exception of first-generation feedstocks which were found to be most unsustainable due to their risk to the global food supply. The review emphasised that various opportunities were present in the different alternative biodiesel sources. Biodiesel feedstock selection is mainly attributed to the availability of the feedstock, economic viability, biodiesel production processes and the climatic conditions in present area for plant-based oils. While many of the feedstocks have limitations due to fuel properties and FFA content, blending has been found to be a favourable practice in diesel substitution.

5. Future work

This review highlights and summarizes the opportunity in biodiesel production from various feedstocks. From the literature analysed, it is found that there are various factors that influence choice of feedstocks, including oil yield, composition and feedstock availability. These avail different research opportunities in the area of feedstock choice and feasibility. Therefore, in future, research should focus on the choice of feedstocks, identifying feedstocks with a high yield and environmental and socio-economic feasibility of feedstocks. The review paper is a step towards a research that is currently being conducted on the production of biodiesel from *Jatropha curcas* and micro algae as alternative sources of biodiesel. The two sources are available in Botswana hence a focus on them.

References

[1] Singh D, Sharma D, Soni SL, Sharma S, Kumar Sharma P, and Jhalani A. A review on feedstocks, production processes, and yield for different generations of biodiesel. Fuel, 2020; 262: 116553.

[2] Singh SP and Singh D. Biodiesel production through the use of different sources and characterization of oils and their esters as the substitute of diesel: A review. Renew. Sustain. Energy Rev, 2010; 14(1): 200–216.

[3] Brennan L and Owende P. Biofuels from microalgae-A review of technologies for production, processing, and extractions of biofuels and co-products. Renew. Sustain. Energy Rev, 2010; 14(2): 557–577.

[4] Mata TM, Martins AA, and Caetano NS. Microalgae for biodiesel production and other applications: A review. Renew. Sustain. Energy Rev, 2010; 14(1): 217–232.

[5] Saeed S, Ashour I, and Ali MRO. Fast pyrolysis of Jatropha seeds in a fixed bed furnace. Pet. Coal, 2019; 61(6): 1494–1504.

[6] Dufey A. Biofuels production, trade and sustainable development: emerging issues, International Institute for Environment and Development, London. September 2006 (2).

[7] Vogel CFA, Kado SY, Kobayashi R, Liu X, Wong P, Na K, Durbin T, Okamoto RA, and Kado NY. Inflammatory marker and aryl hydrocarbon receptor-dependent responses in human macrophages exposed to emissions from biodiesel fuels. Chemosphere, 2019; 220: 993–1002.

[8] Aransiola EF, Ojumu TV, Oyekola OO, Madzimbamuto TF, and Ikhu-Omoregbe DIO. A review of current technology for biodiesel production: State of the art. Biomass and Bioenergy, 2014; 61: 276–297.

[9] Liu K and Wang R. Biodiesel production by transesterification of duck oil with methanol in the presence of alkali catalyst. Pet. Coal, 2013; 55(1): 68–72.

[10] Demirbas A. New liquid biofuels from vegetable oils via catalytic pyrolysis. Energy Educ. Sci. Technol, 2008; 21(1): 1–59.

[11] Nautiyal P, Subramanian KA, and Dastidar MG. Production and characterization of biodiesel from algae. Fuel Process. Technol., 2014; 120: 79–88.

[12] Mahdavi M, Abedini E, and hosein Darabi A. Biodiesel synthesis from oleic acid by nanocatalyst (ZrO2/Al2O3) under high voltage conditions. RSC Adv, 2015; 5(68): 55027–55032.

[13] Balat M. Potential alternatives to edible oils for biodiesel production - A review of current work. Energy Convers. Manag, 2011; 52(2): 1479–1492

[14] Peer MS, Kasimani R, Rajamohan S, and Ramakrishnan P. Experimental evaluation on oxidation stability of biodiesel/diesel blends with alcohol addition by Rancimat instrument and FTIR spectroscopy. J. Mech. Sci. Technol, 2017; 31(1): 455–463.

[15] Azam MM, Waris A, and Nahar NM. Prospects and potential of fatty acid methyl esters of some non-traditional seed oils for use as biodiesel in India. Biomass and Bioenergy, 2005; 29(4): 293–302.

[16] Kamel DA, Farag HA, Amin NK, Zatout AA, and Ali RM. Smart utilization of jatropha (Jatropha curcas Linnaeus) seeds for biodiesel production: Optimization and mechanism. Ind. Crops Prod., 2018; 111(December 2017): 407–413.

[17] Tariq M, Ali S, and Khalid N. Activity of homogeneous and heterogeneous catalysts, spectroscopic and chromatographic characterization of biodiesel: A review. Renewable and Sustainable Energy Reviews, 2012; 16(8): 6303–6316.

[18] Siqueira SF, Francisco EC, Queiroz MI, De Menezes CR, Zepka LQ, and Jacob-Lopes E. Third generation biodiesel production from microalgae *Phormidium autumnale*. Brazilian J. Chem. Eng, 2016; 33(3): 427–433.

[19] Atabani AE, Silitonga AS, Ong HC, Mahlia TMI, Masjuki HH, Badruddin IA, and Fayaz H. Non-edible vegetable oils: A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. Renew. Sustain. Energy Rev, 2013; 18(C): 211–245.

[20] Bart JCJ, Palmeri N, and Cavallaro S. Feedstocks for biodiesel production. Woodhead Publishing Series in Energy, December 2010; 130–225.

[21] Thapa S, Indrawan N, and Bhoi PR. An overview on fuel properties and prospects of Jatropha biodiesel as fuel for engines. Environmental Technology and Innovation, 2018; 9 (Feb): 210–219.

[22] Ong HC, Mahlia TMI, Masjuki HH, and Norhasyima RS. Comparison of palm oil, *Jatropha curcas* and *Calophyllum inophyllum* for biodiesel: A review. Renewable and Sustainable Energy Reviews, 2011; 15(8): 3501–3515.

[23] Akbar E, Yaakob Z, Kamarudin SK, and Salimon J. Characteristic and Composition of Jatropha Curcas Oil Seed from Malaysia and its Potential as Biodiesel Feedstock Feedstock. European Journal of Scientific Research, 2009; 29(3): 396-403.

[24] Gunstone FD. Rapeseed and canola oil : production, processing, properties and uses. Blackwell Pub. ; CRC Press, Oxford, EN; Boca Raton, FL, 2004.

[25] Edem DO. Palm oil: Biochemical, physiological, nutritional, hematological, and toxicological aspects: A review. Plant Foods for Human Nutrition, 2002; 57(3–4): 319–341.

[26] Jain S, The current and future perspectives of biofuels. Biomass, Biopolymer-Based Materials, and Bioenergy: Construction, Biomedical, and other Industrial Applications Elsevier Ltd, 2019; Chapter 21;495-517.

[27] Kgathi DL, Mmopelwa G, Chanda R, Kashe K, and Murray-Hudson M. A review of the sustainability of Jatropha cultivation projects for biodiesel production in southern Africa: Implications for energy policy in Botswana. Agric. Ecosyst. Environ, 2017; 246(May): 314–324.

[28] Locke A and Henley G. Scoping report on biofuels projects in five developing countries. London, 2013.

[29] Rapier R. Renewable diesel. Biofuels, Solar and Wind as Renewable Energy Systems: Benefits and Risks, Springer Netherlands, 2008; Chapter 7; pp. 153–171.

[30] Scott PT, Pregelj L, Chen N, Hadler JS, Djordjevic MA, and Gresshoff PM. Pongamia pinnata: An Untapped Resource for the Biofuels Industry of the Future. BioEnergy Res, 2008; 1(1): 2–11.

[31] Ahmad M, Zafar M, Khan MA, and Sultana S. Biodiesel from Pongamia pinnata L. Oil: A promising alternative bioenergy source. Energy Sources, Part A Recover. Util. Environ. Eff, 2009; 31(16): 1436–1442.

[32] Sharma YC, Singh B, and Upadhyay SN. Advancements in development and characterization of biodiesel: A review. Fuel, 2008; 87(12): 2355–2373.

[33] Sharma YC, Singh B, and Korstad J. High Yield and Conversion of Biodiesel from a Nonedible Feedstock (Pongamia pinnata). J. Agric. Food Chem*,* 2010; 58(1): 242–247.

[34] Raheman H and Phadatare AG. Diesel engine emissions and performance from blends of karanja methyl ester and diesel. Biomass and Bioenergy, 2004; 27(4): 393–397.

[35] Singh J and Saxena RC. An Introduction to Microalgae: Diversity and Significance. Diversity and Significance. Handbook of Marine Microalgae: Biotechnology Advances, Elsevier Inc, 2015; Chapter 2; pp. 11–24.

[36] Heimann K and Huerlimann R. Microalgal Classification: Major Classes and Genera of Commercial Microalgal Species. S.-K. B. T.-H. of M. M. Kim, Ed. Boston: Academic Press, 2015; Chapter 3; pp. 25–41.

[37] Ferrell J and Sarisky-Reed V. National Algal Biofuels Technology Roadmap. United States, May 2010.

[38] Li Y, Horsman M, Wu N, Lan CQ, and Dubois-Calero N. Biofuels from microalgae. Biotechnol. Prog, 2008; 24(4): 815–820.

[39] Knothe G and Steidley KR. A comparison of used cooking oils: A very heterogeneous feedstock for biodiesel. Bioresour. Technol, 2009; 100(23): 5796–5801.

[40] Kulkarni MG and Dalai AK. Waste Cooking Oil, An Economical Source for Biodiesel: A Review. Ind. Eng. Chem. Res, 2006; 45(9): 2901–2913.

[41] Wang Y, Pengzhan Liu SO, and Zhang Z. Preparation of biodiesel from waste cooking oil via two-step catalyzed process. Energy Convers. Manag, 2007; 48(1): 184–188.

To whom correspondence should be addressed: Tumeletso Lekgoba, Department of Chemical, Materials and Metallurgical Engineering, Botswana International University of Science and Technology, Palapye, Botswana, E-mail: lekgobat@biust.ac.bw