Biodiesel Sustainability: The Global Impact of Potential Biodiesel Production on the Energy-Water-Food (EWF) Nexus

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Abstract

A data-driven model is used to analyse the global effects of biodiesel on the energy-water-food (EWF) nexus, and to understand the complex environmental correlation. Several criteria to measure the sustainability of biodiesel and four main limiting factors for biodiesel production are discussed in this paper. The limiting factors includes water stress, food stress, feedstock quantity and crude oil price. The 155-country model covers crude oil prices ranging from USD10/bbl to USD160/bbl, biodiesel refinery costs ranging from -USD0.30/L to USD0.30/L and 45 multi-generation biodiesel feedstocks. The model is capable of ascertaining changes arising from biodiesel adoption in terms of light-duty diesel engine emissions (NO, CO, UHC and smoke opacity), water stress index (WSI), dietary energy supply (DES), Herfindahl-Hirschman index (HHI) and short-term energy security. With the addition of potential biodiesel production, the renewable energy sector of global primary energy profile can increase by 0.43%, with maximum increment up to 10.97% for Malaysia. At current crude oil price of USD75/bbl and refinery cost of USD0.1/L, only Benin, Ireland and Togo can produce biodiesel profitably. The model also shows that water requirement varies non-linearly with multi-feedstock biodiesel production as blending ratio increases. Out of the 155 countries, biodiesel production is limited by feedstock quantity for 82 countries, 47 are limited by crude oil price, 20 by water stress and 6 by food stress. The results provide insights for governments to set up environmental policy guidelines, in implementing biodiesel technology as a cleaner alternative to diesel.

Keywords: Biodiesel, Sustainability, EWF nexus, Water stress, Food stress

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1. Introduction

Global primary energy demand has been increasing at a rate of 1.8% per annum since 2005 (Sharma and Singh, 2017) and reached more than 13,500 Mtoe in 2017 (BP, 2017; Enerdata, 2018), while petroleum fuel (the main transport fuel) is facing imminent depletion in 50 years based on the usage trends and proven reserves (Day and Day, 2017; BP, 2018; World Coal Association, 2018). Renewable energy sources made up the mix of the main solutions to solve this energy crisis. On the environmental aspect, renewable energy is currently the only option in the power sector that has decarbonising potential to limit global temperature rise to 2°C above pre-industrial level, as aimed by the 2015 Paris Agreement (Nations, 2015; Commission, 2016). The increasing energy demand and environmental concern have necessitated the use of cleaner and more sustainable energies, including biofuels such as biodiesel, bioethanol, biogas and biohydrogen (Sharma and Singh, 2017; Živković and Veljković, 2018). The European Union targeted an overall 20% renewable energy share in energy consumption by 2020 (Commission, 2016). In 2016, the European Commission proposed to further raise its target to 27% by 2030 to meet the 2015 Paris Agreement. It was reported that only 12.9% of the global primary energy was from renewable sources in 2015, including biofuels and wastes, geothermal, solar and hydropower (IEA, 2015).

Biodiesel has been widely studied as a renewable replacement fuel for petroleum diesel since the past few decades (Budin, Breene and Putnam, 1995; Machacon *et al.*, 2001; Myint and El-Halwagi, 2009; Noor *et al.*, 2016; Živković and Veljković, 2018). As a diesel substitute, biodiesel has been proven to be more beneficial in terms of emissions and renewability. However, the sustainability of biodiesel has yet to be defined. Food-crops and water are the two main consumptions during biodiesel production, while the effects of biodiesel production on the supply chains of these two resources are still unclear. As water and food form the basic human needs, the impact on these two sectors will patently influence biodiesel sustainability. In order to understand the complex interaction between biodiesel production and both water and food securities, it is necessary to consider biodiesel in the energy-water-food (EWF) nexus.

Transportation sector is the second largest energy consumer in the world at 35% of the global primary energy in 2017 (IEA, 2017) and it is one of the major sources of greenhouse gas (GHG)

emissions (Sharma and Singh, 2017). Gasoline and diesel are respectively the first and second major transport fuels (EIA, 2017), while diesel's growth rate has outpaced that of gasoline of late (Naylor and Higgins, 2017). Correspondingly, the production growth rate of biodiesel, as diesel substitute, has been significantly higher than that of ethanol, the gasoline substitute, since 2005. In 2017, bioethanol production saw an annual increase of 2.5% while biodiesel was increasing at 9% (REN21, 2018). Biodiesel production has increased by seven times from 2005 to 2015 and there is an expectation of another 35% growth by 2025 (Naylor and Higgins, 2018). A range of biodiesel blendings from B2 to B8 have been achieved (and continue to grow) in 2015 by large energy consumers including Argentina, Brazil, Canada, Colombia, the EU, Indonesia, Malaysia, Thailand and the US. The use of biodiesel, either in its neat form or blended with diesel, has helped countries to improve the energy supply in both quantity and diversity.

Biodiesel is known to have better emission properties than diesel. One of the main features that differentiates biodiesel from diesel is the presence of fuel-bound oxygen. Biodiesel contains 10-15 wt.% of oxygen, depending on the feedstock used (Canoira *et al.*, 2010; Viola, Zimbardi and Valerio, 2011; Ng, Ng and Gan, 2012; Silitonga, Ong, *et al.*, 2013). The oxygen content in biodiesel results in higher flame temperature and more complete combustion in conventional CI engine (Datta and Mandal, 2017). These factors significantly affect the emission for blended biodiesel-diesel combustion. Although the addition of oxygen content from biodiesel increases the CO_2 formation in biodiesel-diesel combustion, the production of biodiesel feedstocks captures CO_2 via photosynthesis to offset the CO_2 emitted during burning. Using life-cycle analysis, the potential to reduce 50-78% of CO_2 output for biodiesel has been evidently proven (Myint and El-Halwagi, 2009; Živković and Veljković, 2018). Toxic air pollutants such as particulate matter (PM) and unburned hydrocarbons (UHCs) can be reduced by 90% and 20-40% with the use of neat biodiesel and B20, respectively (Abbasi and Diwekar, 2014). PM forms through incomplete combustion and the burning of lubrication oil (Datta and Mandal, 2017). High temperature and pressure in the fuel-rich zone lead to formation of smoke. These two pollutants can be reduced by the fuel-bound oxygen of biodiesel in the fuel-rich zone. On the other hand, the drawback of biodiesel is the increase of thermal NO_x emission (11-30%) due to additional oxygen content and the higher flame temperature (Myint and El-Halwagi, 2009; Datta and Mandal, 2017). Despite the

increment on NO_x emission, the overall effect of biodiesel usage on the environment is considered beneficial.

Apart from the advancements in aspects of energy source and environment, studies have proven the potential of biodiesel on the near one-to-one replacement for diesel (Abbasi and Diwekar, 2014). It was found that the energy return of fossil fuel input on biodiesel production ranges from 2.5 to 3.5. Fossil fuel is consumed during biodiesel production process such as transportation, on-farm machinery and fertiliser production. A one-to-one displacement of fossil energy with biodiesel can be achieved on a life-cycle basis. Furthermore, the similarities between diesel and biodiesel properties allow the substitutional fuel to be used without the need for engine modification. A B20 fuel can be applied directly with ease. The ultralow sulphur diesel (ULSD) standard required diesel to have sulphur content below 15ppm. Sulphur removal process will remove some natural lubricants in diesel, such as oxygen, nitrogen and aromatics (Hu, Zhang and Li, 2017). (Muñoz *et al.*, 2011) reported that ULSD fuel lubricity can be improved to 338μm wear scar diameter (WSD) with as low as 100ppm biodiesel addition, whereas pure diesel fuel with 10ppm sulphur content would show a WSD of more than 500ηm (Nicolau *et al.*, 2014). Another study showed that biodiesels with lower mono-saturation level exhibit better friction modifier effect for boundary and elasto-hydrodynamic lubrication regimes while reducing the load carrying capacity along mixed lubrication regime (Hamdan *et al.*, 2017). Coconut biodiesel, with the lowest mono-saturation level, has the best friction modifier effect among the tested fuels while the worst load carrying capacity. On the other hand, soybean biodiesel would be a better bio-lubricant/additive, showing more balanced lubrication properties. The improved lubrication would lead to better engine operation, in terms of efficiency and lifespan (Myint and El-Halwagi, 2009).

Besides the benefits of using biodiesel as a fuel, having renewable and sustainable sources is a potent criterion for a sustainable production. Different possible sources for biodiesel production have been explored. The three common feedstocks include edible oils (vegetable oil and animal fat), non-edible oil (such as waste cooking oil, jatropha oil, camelina oil) and microalgae, which respectively represent the first, second and third generation of biodiesel feedstock (Elms and El-Halwagi, 2010; Mata *et al.*, 2011; Abbasi and Diwekar, 2014; Sharma and Singh, 2017; Hasan and Avami, 2018; Nabi and Rasul, 2018). All of these sources are considered renewable, however, there are different issues

associated with each of them. First-generation biodiesel is the most common and its production often leads to the well-known food-fuel debate, with influences on both the supply and prices (Naylor and Higgins, 2018). Non-edible second-generation biodiesel feedstocks can be grown on non-arable land, although lands for food production can be saved, it still requires more study for the feasibility and productivity (Hasan and Avami, 2018). Microalgal biodiesel has high production and contributes to lower emissions, while the water consumption could be more than double of the first and second generation, and technologies involving cultivation, oil extraction and harvesting need to be further improved (Sharma and Singh, 2017).

An analytical predicting study has arisen from the concerns of food security, emission and water requirement for biodiesel as a renewable energy in Iran (Hasan and Avami, 2018). As the world 10th largest GHG producer in 2012, the country has been taking actions to mitigate its carbon footprint. The authors analysed three scenarios for biodiesel production in the water-energy-emission nexus with the aim to obtain optimal pathways to satisfy the B2 (2% biodiesel blend) energy demand. In order to not disturb the food security, non-edible second and third generation feedstocks like jatropha and microalgae are chosen for biodiesel production in each scenario. The cost, emission and water requirement throughout the production were respectively minimised in the three scenarios. It is reported that, in Iran, GHG emission can be reduced by the use of biodiesel (especially microalgal biodiesel) while water consumption during biodiesel production will limit the available water supply for other human uses.

Food security can be correlated to the arable land (Irabien and Darton, 2016). The land can be seen as a medium to store, convert and provide energy for food production. A research analysed the food-energy nexus through the case study of the on-farm energy generation in Miyagi, Japan (Cuberos Balda, Furubayashi and Nakata, 2017). Miyagi is a prefecture with the largest abandoned land (9720 ha) in Japan since the 2011 earthquake. The case study proposed to utilise the abandoned land with self-sufficient farms by growing crops for food and biofuel production. By setting the priority to meet the local food demand and using the surplus land to produce biofuel feedstocks, there could be a net improvement in both food security and energy security. The research showed that 5247 kL/year of bioethanol can potentially be produced to substitute current gasoline demand with E5 fuel (5%

bioethanol and 95% gasoline) in buses, regular cargo and 53% of small cargo in Miyagi. The utilisation of energy self-sufficient farms would bring multiple positive impacts, including reduction in the dependency on fossil fuels and food import, job generation and increase in food security and local fuel access.

(Gilron, 2014) mentioned the typical example of water-energy nexus for power generation and water desalination at coastal area. As energy production consumes water and at the same time water treatment uses energy, water has been both the sink and source of energy. Energy production has become an increasingly large water consumer, and biodiesel production is no exemption. Another study about EWF nexus also portrayed the interlinkage of the three elements via a greenhouse tomato production case study (Irabien and Darton, 2016). Fresh water is required in cultivating crops (whether it is food- or energy-crop) as well as in energy production and conservation; energy is used in water treatment, food processing and transportation of both water and food; and crops can be converted to food and fuel while agriculture can be competing for land use with water system. The water footprint for each biofuel production varies significantly with the feedstock used as well as the production region (Xie *et al.*, 2017). Selections for feedstocks and production pathways according to local conditions, such as climate and crop yield, will play important roles in the energy-water relationship. According to (Irabien and Darton, 2016), in order to achieve a sustainable EWF system, all three elements must be able to provide availability, accessibility and utilisation (AAU) for human well-being, while assuring the extent and diversity of the ecosystems on the planet in space and time.

Researches have shown the capability of biodiesel as replacement fuel for diesel. Many studies have tried to understand the correlation between energy production and basic natural resources such as water and food. In this study, a data-driven model is developed to investigate the potential and the global impact of biodiesel production on the EWF nexus. Two main categories of biodiesel feedstocks are considered: edible oil and non-edible oil, which respectively represents the first and second-generation biodiesel feedstock. As the first-generation feedstock is dominant in the current biodiesel production, the report focused on the potential effect of the first generation biodiesel on various aspects, including the limiting factors in the EWF nexus, emissions, energy diversity and energy security. Generation replacement of biodiesel feedstock is also considered in term of the plausible arable land saving. The

results of this study can serve as a reference for governments to set up policies regarding to biodiesel production in each country.

2. Methodology

In this data-driven model, potential biodiesel production of 155 countries are evaluated under 31 crude oil prices and 13 refinery costs. The crude oil price ranges from USD10/bbl to USD160/bbl with an interval of USD5/bbl, while the refinery cost is set from –USD0.30/L to USD0.30/L with a USD0.05/L interval. There are 14 first-generation biodiesel feedstocks selected, including coconut, cottonseed, groundnut, kapok, maize, palm, olive, palm kernel, rapeseed, safflower, sesame, soybean, sunflower and rice bran (Saladini *et al.*, 2016). Feedstock data, including export quantity (FAO, 2016b), export value (FAO, 2016c) and crop yield (FAO, 2016a), is taken from FAOSTAT for countries all over the world. The 155 countries are then selected due to the completeness of the dataset.

Thailand, Indonesia and Malaysia are the three countries that are focused in this study. Thailand has comparatively spread feedstocks for biodiesel production, including palm, palm kernel and soybean. Indonesia has potential multi-feedstock biodiesel production capability that heavily depends on palm. Biodiesel production in Malaysia, on the other hand, can be fully relied on one single feedstock, which is palm. Thailand, Indonesia and Malaysia represent countries that have potential biodiesel production with lightly skewed multi-feedstock, heavily skewed multi-feedstock and monopolised feedstock in this study, respectively. Throughout the economic setup of the model, 10 feedstocks could be profitable in biodiesel production. This includes coconut, cottonseed, groundnut, maize, palm, palm kernel, rapeseed, safflower, soybean and sunflower. Additionally, second generations such as camelina, jatropha, jojoba, karanja, kenaf, linseed, mahua, moringa and tumba were also evaluated.

3. Potential biodiesel production

3.1 First-Generation Biodiesel

A total of 14 first-generation biodiesel feedstocks are included in this study. The properties of these vegetable oils are presented in Table 1, whereas Table 2 lists out the fuel properties of the 14

biodiesels feedstocks. The oil density is used to calculate the conversion of vegetable oil into biodiesel. The cetane number, kinematic viscosity, carbon residue, oxygen content and density of biodiesel are used to predict the engine-out emissions for light-duty diesel engines.

Table 1: Properties of edible vegetable oil as first-generation biodiesel feedstock.

Feedstock	Oil Content (wt%)	Oil Density (kg/L)	Energy Content (MJ/kg)	Ref.
Coconut	64	0.918	35.00	(Machacon *et al.*, 2001; Karmakar, Karmakar and Mukherjee, 2010)
Palm kernel	54.5	0.922	38.03	(Chuah *et al.*, 2006; Benjapornkulaphong, Ngamcharussrivichai and Bunyakiat, 2009; Karmakar, Karmakar and Mukherjee, 2010)
Palm	45	0.918	40.14	(Agarwal, 2007; Karmakar, Karmakar and Mukherjee, 2010; Kumar, Varun and Chauhan, 2013)
Cottonseed	21.5	0.915	39.65	(Altin, Cetinkaya and Yucesu, 2001; Agarwal, 2007; Karmakar, Karmakar and Mukherjee, 2010)
Rice bran	19	0.919	39.50	(Machacon *et al.*, 2001; Karmakar, Karmakar and Mukherjee, 2010)
Groundnut	50	0.903	39.80	(Agarwal, 2007; Karmakar, Karmakar and Mukherjee, 2010; Verma and Sharma, 2016)
Kapok	26.5	0.921	39.56	(Agarwal, 2007; Senthil Kumar, Senthil Kumar and Annamalai, 2015)
Soybean	17.5	0.914	39.62	(Altin, Cetinkaya and Yucesu, 2001; Agarwal, 2007; Karmakar, Karmakar and Mukherjee, 2010)
Sesame	50	0.913	39.30	(Whittington, 2006; Sinha, Agarwal and Garg, 2008; Russo *et al.*, 2012)
Olive	57.5	0.925	37.00	(Karmakar, Karmakar and Mukherjee, 2010; Kumar, Varun and Chauhan, 2013)
Maize	48	0.910	39.50	(Sinha, Agarwal and Garg, 2008; Karmakar, Karmakar and Mukherjee, 2010; Verma and Sharma, 2016)
Sunflower	30	0.916	39.53	(Altin, Cetinkaya and Yucesu, 2001; Sinha, Agarwal and Garg, 2008; Karmakar, Karmakar and Mukherjee, 2010)

| Rapeseed | 42 | 0.912 | 37.62 | (Altin, Cetinkaya and Yucesu, 2001; Agarwal, 2007; Karmakar, Karmakar and Mukherjee, 2010) |
| Safflower | 40 | 0.914 | 39.50 | (Agarwal, 2007; Onay, 2007; Singh and Singh, 2010) |

Table 2: Fuel properties of first-generation biodiesel.

Feedstock	Biodiesel Density (kg/L)	Energy Content (MJ/kg)	Cetane Number	Kinematic Viscosity (mm2/s)	Carbon Residue (wt%)	Oxygen Content (wt%)	Ref.
Coconut	0.870	35.20	65.80	2.70	0.001	15.10	(Hoekman *et al.*, 2012; Ng, Ng and Gan, 2012)
Palm kernel	0.870	36.50	56.50	2.80	0.087	13.36	(Benjapornkulaphong, Ngamcharussrivichai and Bunyakiat, 2009; Viola, Zimbardi and Valerio, 2011)
Palm	0.874	37.30	67.50	4.40	0.020	11.90	(Hoekman *et al.*, 2012; Ng, Ng and Gan, 2012)
Cottonseed	0.879	38.18	53.30	4.70	0.020	11.13	(Rao *et al.*, 2011; Viola, Zimbardi and Valerio, 2011; Giakoumis, 2013)
Rice bran	0.881	38.05	56.30	4.70	0.230	11.00	(Lin *et al.*, 2009; Viola, Zimbardi and Valerio, 2011; Giakoumis, 2013)
Groundnut	0.883	38.05	54.90	4.77	0.087	10.87	(Viola, Zimbardi and Valerio, 2011; Giakoumis, 2013)
Kapok	0.877	39.40	57.20	4.61	0.029	11.04	(Silitonga, Masjuki, *et al.*, 2013; Silitonga, Ong, *et al.*, 2013; Senthil Kumar, Senthil Kumar and Annamalai, 2015)
Soybean	0.885	37.00	51.00	4.00	0.005	11.50	(Hoekman *et al.*, 2012; Ng, Ng and Gan, 2012)
Sesame	0.867	40.40	50.48	4.20	0.039	10.92	(Karmakar, Karmakar and Mukherjee, 2010; Viola, Zimbardi and Valerio, 2011; Sarve,

							Sonawane and Varma, 2015)
Olive	0.881	37.29	58.90	5.05	0.220	10.92	(Viola, Zimbardi and Valerio, 2011; Giakoumis, 2013; Noor *et al.*, 2016)
Maize	0.882	38.60	52.50	4.32	0.087	10.97	(Viola, Zimbardi and Valerio, 2011; Giakoumis, 2013)
Sunflower	0.883	37.80	51.90	4.53	0.050	10.92	(Sinha, Agarwal and Garg, 2008; Viola, Zimbardi and Valerio, 2011; Giakoumis, 2013)
Rapeseed	0.882	37.63	54.10	4.63	0.010	10.87	(Schober and Mittelbach, 2004; Viola, Zimbardi and Valerio, 2011; Giakoumis, 2013)
Safflower	0.884	38.15	51.80	4.10	0.087	10.90	(Viola, Zimbardi and Valerio, 2011; Giakoumis, 2013)
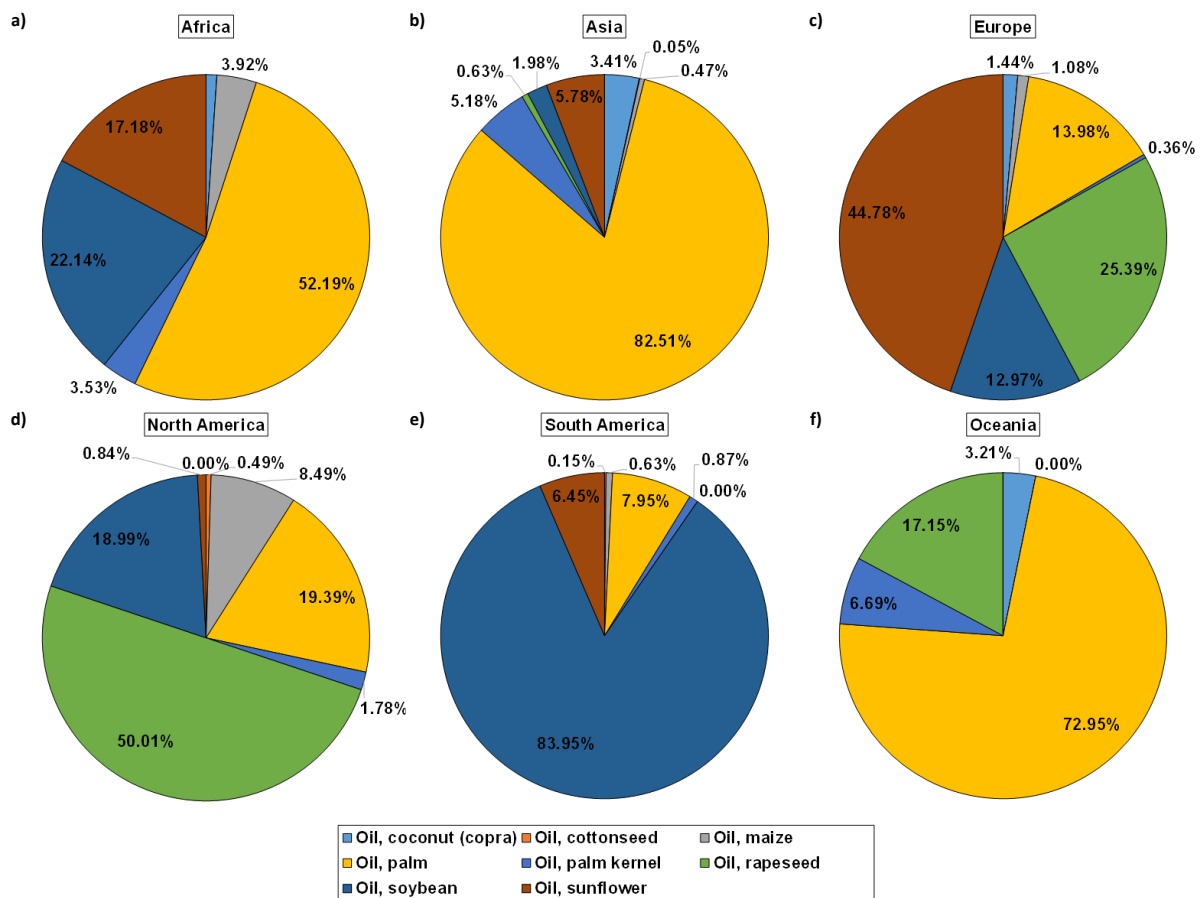
Figure 1: Proportion of potential first-generation feedstock at continental level for (a) Africa (b) Asia (c) Europe (d) North America (e) South America (f) Oceania.

==Figure 1 shows the proportion of potential first-generation feedstock at continental level based on the amount of oil extracted. From it, the two main potential biodiesel feedstocks in the world are oil palm and soybean.== Both feedstocks are oilseed crops, with the highest oil production worldwide. On continent basis, the potential biodiesel that can be produced from the feedstocks selected in this study for Asia and Oceania will be monopolised by palm with the proportion of 83% and 73%, respectively. Africa has 52% of its biodiesel feedstocks contributed from palm. In South America, soybean is the dominant feedstock with a proportion of 84%, whereas in North America the major feedstock is rapeseed with a proportion of 50%. However, the variations of feedstock in Europe is relatively well-spread. On country basis, as shown in Figure 2, out of the 84 countries that can potentially produce biodiesel, palm would be the dominant feedstock in 23 countries, rapeseed in 17 countries, sunflower

in 14 countries and 7 other feedstocks spread among 30 countries. <mark>The potential feedstock quantity at this point shows the upper limits for conversion into biodiesel. In reality, it will face competition from other sectors like the food industry and intra-sector cross-usage for other sustainable liquid biofuels.</mark>

The current biodiesel production shows that 13 major biodiesel-producing countries with a minimum biodiesel production of 10,000 barrels per day are the United States, Brazil, Indonesia, Germany, Argentina, France, Spain, Thailand, Poland, Singapore, Belgium, the Netherlands and Colombia (EIA, 2016). With the potential feedstocks, these countries have immense potential to increase the production of biodiesel by a large volume. For instance, countries such as Indonesia, Malaysia, Argentina, Ukraine, Canada, the Netherlands, Russian Federation, Germany, the United States, Spain and Brazil can potentially produce 1×10^9 litres of biodiesel per annum.
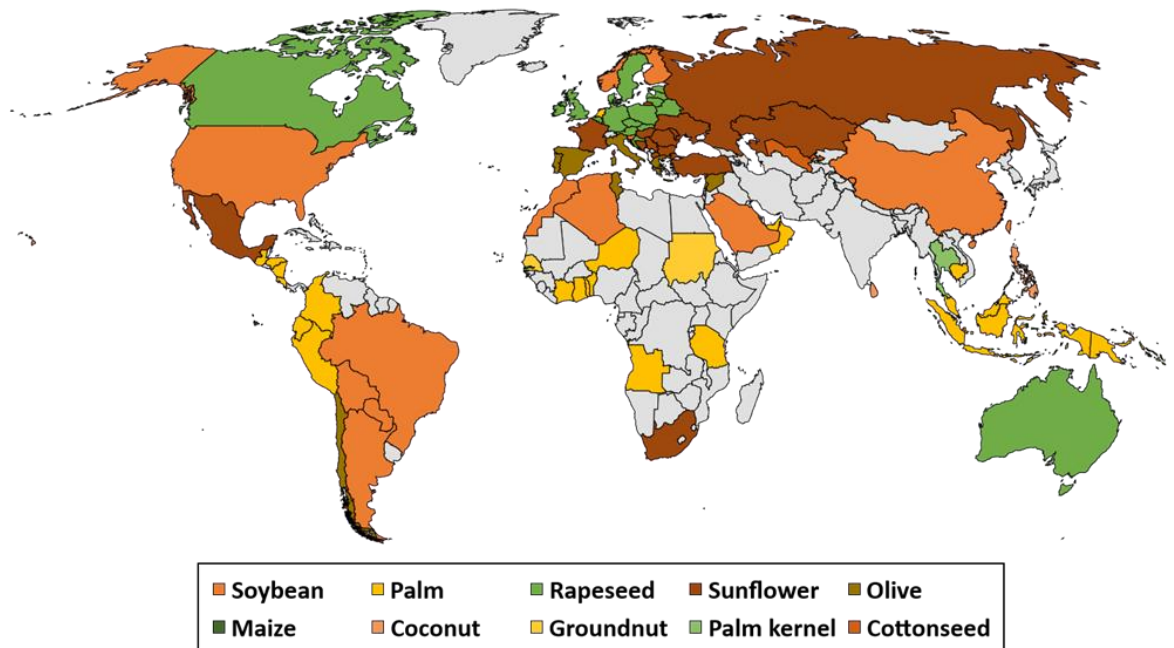

Figure 2: Potential dominant first-generation biodiesel feedstock of each country.

Potential biodiesel volume (PBV_{ij}) for each feedstock and country is calculated:

$$PBV_{ij} = LV_{ij} \times CR \qquad \text{(Eq.1)}$$

$$LV_{ij} = \frac{EQ_{ij} \times 1000}{OD_i} \qquad \text{(Eq.2)}$$

where LV_{ij} is the lipid volume of each of the potential biodiesel feedstocks in different countries, and CR (0.98) is the volumetric conversion ratio from oil to biodiesel (Johnston and Holloway, 2007; O'Keeffe *et al.*, 2017) EQ_{ij} is the export quantity of each feedstock, and OD_i is the oil density. A minimum threshold value of 10,000 tonnes has been set for the export quantity. Any export quantity of vegetable oils that is lower than the threshold is considered to be inadequate for the potential biodiesel production. The threshold value is based on a generic biodiesel plant with a capacity of 10 million litres per annum (USDA, 2017). The export quantity which reaches the threshold value is used in the calculation of the potential biodiesel production.

By summing up the total potential biodiesel production, $TPBV_j$ with the current biodiesel production, CBV_j, the total biodiesel volume, TBV of a country can be obtained. Figure 3 shows the total biodiesel volume against the current annual diesel consumption of each country (EIA, 2014). The countries which locate above the B100 line indicate that the total biodiesel volume can fully replace the current diesel consumption on volumetric basis. The B10 and B1 lines respectively represent the total biodiesel volume of 10% and 1% diesel replacement. The only country which is capable to produce sufficient biodiesel to totally replace diesel is Malaysia, followed by Indonesia with a volumetric blending ratio of 88%. There are another 25 countries that can potentially achieve B10, including nine European countries such as Ukraine, the Netherlands, Lithuania and Hungary, whereas 45 countries can reach the B1 line. The majority of European countries are scattered between the B1 and B10 lines, this shows that European countries have potential to add biodiesel into their energy mix.
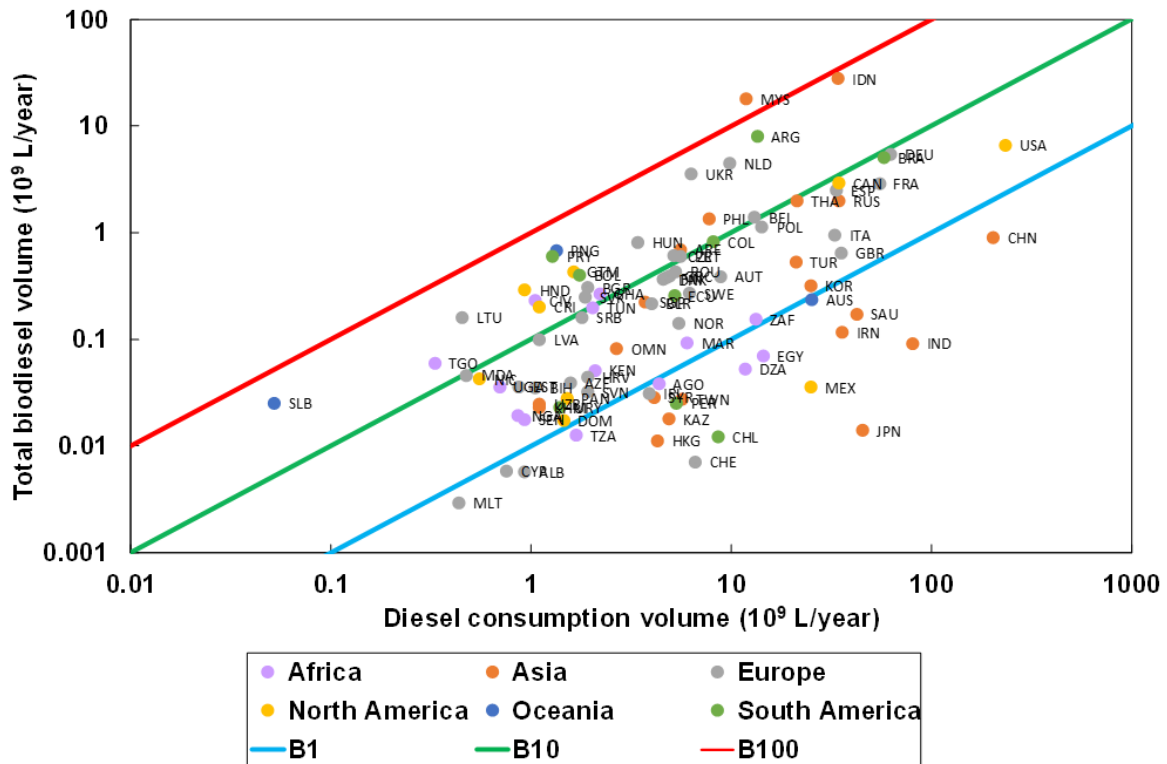
Figure 3: Total first-generation biodiesel volume against diesel consumption volume of all countries with potential feedstock, with lines representing level of blending ratio (B1, B10 and B100).

Figure 4 shows the primary energy profile of the world and Malaysia, with and without the potential biodiesel production (IEA, 2015). At present, the total global renewable energy is 72.12×10^{12} MJ. By introducing the total potential biodiesel volume from all countries into the energy market, the value can be increased to 74.90×10^{12} MJ. Currently in Malaysia, the energy from biofuels and waste is 2.34% of the total primary energy, but with the potential biodiesel volume of 15.9×10^9 litres, the value can be raised to 13.45%. Hence, the energy sources in Malaysia could become more diverse, at the same time, decreasing the dependency on fossil fuels.
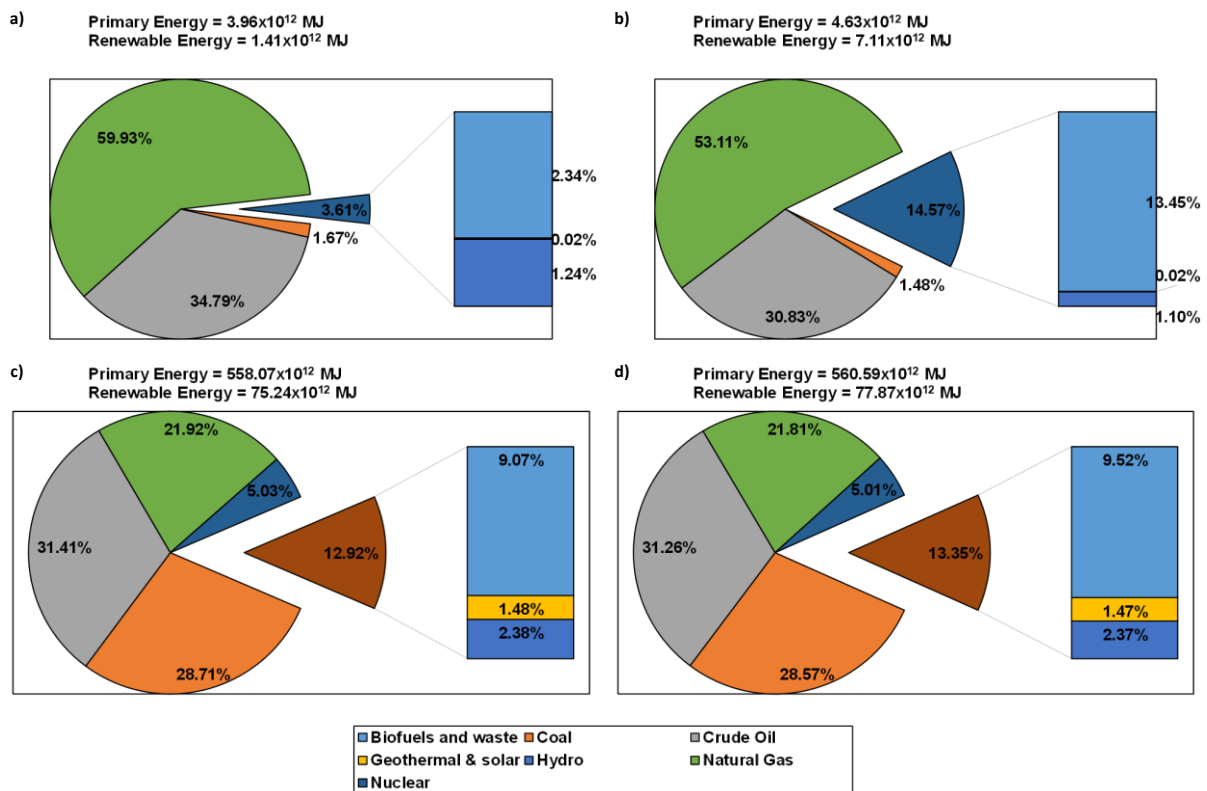
Figure 4: Primary energy profile for a) Malaysia, current condition b) Malaysia, with potential biodiesel volume c) world, current condition d) world, with potential biodiesel volume.

3.2 Second-generation biodiesel - replacement

Second-generation biodiesel is produced from non-food biomass (Saladini *et al.*, 2016). The oils produced will not affect the supply in food market. In this model, 10 second-generation biodiesel feedstocks, namely jatropha, camelina, castor bean, tumba, linseed, jojoba, kenaf, karanja, moringa, and mahua, are evaluated. Feedstock with the most crop yield available natively in each of the 130 countries evaluated for second-generation biodiesel will be selected as the potential dominant second-generation feedstock (as shown in Figure 5). Jatropha is a superior feedstock as it is the potential dominant feedstock in 62 out of 130 countries. Jatropha can be easily cultivated without intensive care in lands that are not suitable for food crops, thus it has wider distribution in the world. Furthermore, camelina is also an outstanding feedstock in almost all European countries (Gui, Lee and Bhatia, 2008).
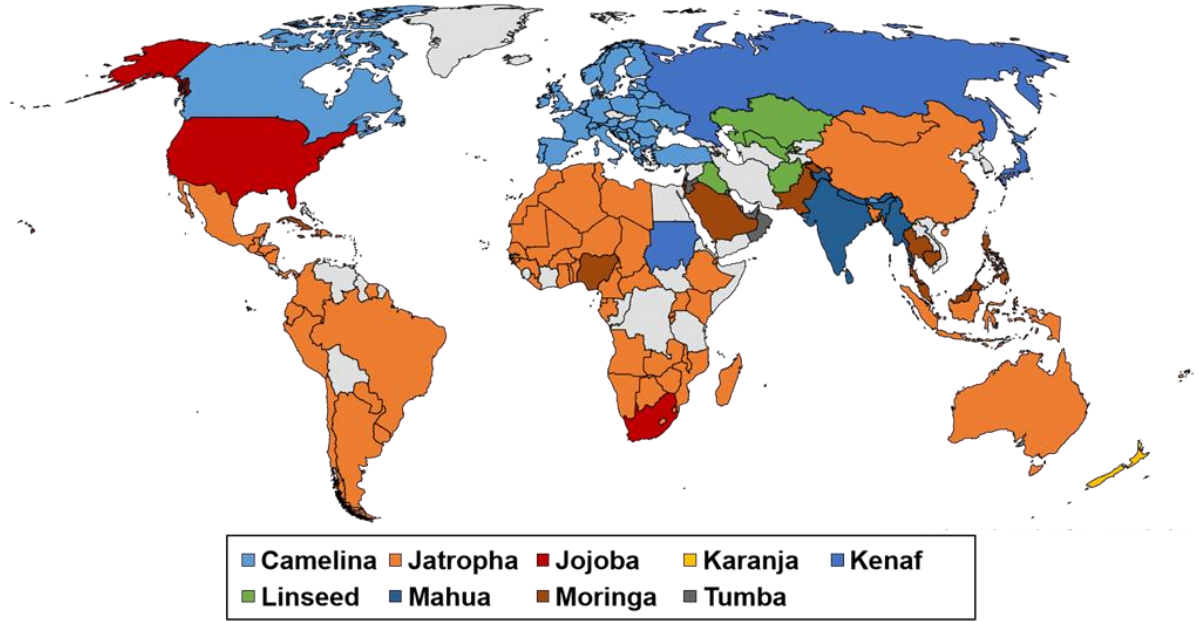
Figure 5: Potential dominant second-generation biodiesel feedstock of each country.

The total plantation area of first-generation feedstock (TPA_j) to produce the total potential biodiesel volume is determined as follow:

$$TPA_j = \sum_i \frac{EQ_{ij} \times 1000}{CY_{ij} \times OC_i} \qquad \text{(Eq. 3)}$$

where CY_{ij} and OC_i are the crop yield and oil content of the feedstocks, respectively. The crop yield of each first-generation feedstock which is obtained from FAOSTAT varies for different countries (FAO, 2016a).

The land area required by second-generation feedstocks (SPA_j) to produce the same volume of total potential biodiesel volume is calculated:

$$SPA_j = \frac{TPBV_j \times OD_i}{CY_i \times OC_i \times CR} \qquad \text{(Eq. 4)}$$

The land area saved by replacing first-generation feedstock with second-generation feedstock, $TASS_j$ can then be equated by deducting SPA from TPA. Figure 6 shows the land area saved by replacing the first-generation feedstock with second-generation feedstock in seven countries. More than 15 million hectares of plantation area can be saved in Indonesia and Malaysia, by replacing all the first-generation feedstocks with jatropha and moringa, respectively. Second-generation biodiesel feedstocks

can be planted in non-arable lands and do not compete for lands with food crops, making them good candidates to replace first-generation feedstocks.
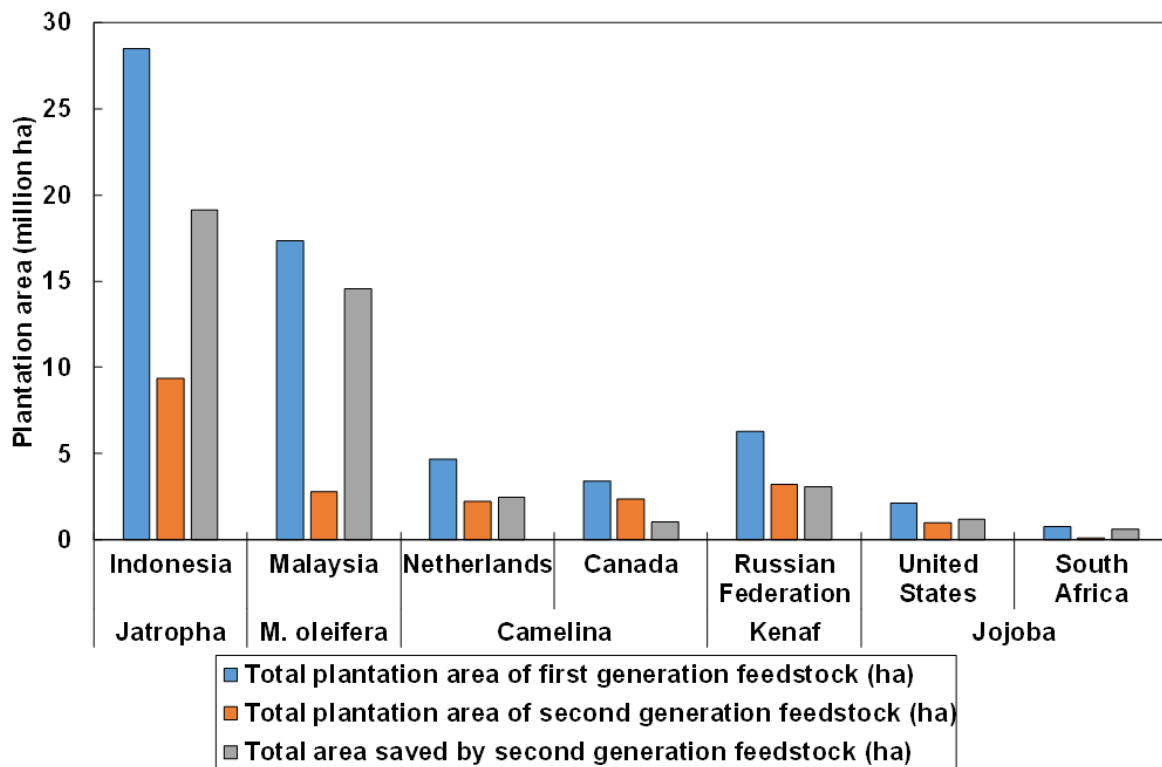

Figure 6: The area saved by replacing all first-generation feedstocks with second-generation feedstocks to produce equal volume of total potential biodiesel, regardless of profitability.

4. Profitable potential biodiesel production

4.1 Government subsidy support

With the current crude oil market and technologies, crude oil price fluctuates at about USD75/bbl (IndexMundi, 2017), and biodiesel can be produced at a refinery cost of USD0.1/L (Gomaa and Abed, 2017). At this situation, Benin, Ireland and Togo are the only countries that can increase biodiesel production profitably without governmental subsidy. In order to increase profitable biodiesel production, it is necessary for the government to provide subsidy to biodiesel industry. According to the combinations of feedstock availability-profitability for each country, different levels of subsidy is needed. As the subsidy increases, various feedstocks become profitable, thus, increase the profitable potential production that can be achieved. The subsidy required is calculated to match the profitability at different level of crude oil price. At crude oil price of USD75/bbl, the equivalent subsidy is zero. The

equivalent subsidies at crude oil prices of USD110/bbl and USD160/bbl are USD0.28/L and USD0.67/L, respectively.

Table 3 lists the global proportion of feedstock used, as a percentage of total biodiesel volume the feedstocks can produce at zero subsidy, USD0.28/L and USD0.67/L. A subsidy of zero reflects the current profitability of biodiesel industry, where only 14 countries have potential for profitable production. Among the 10 feedstocks that can be used to produce profitable biodiesel, palm and rapeseed have lower feedstock cost. As palm has much higher quantity, it is the dominant feedstock at zero subsidy. At higher subsidy (USD0.28/L and above), palm remains the dominant profitable biodiesel feedstock. At subsidy of USD0.28/L, 66.67% of the profitable biodiesel produced is palm biodiesel, and 57.38% at subsidy of USD0.67/L.

Table 3: Proportion of feedstock that could be used in global biodiesel production, in percentage of total feedstock, at zero subsidy and subsidies of USD0.28/L and USD0.67/L.

	Proportion of feedstock use (%)		
Feedstock	Subsidy = 0	Subsidy = USD0.28/L	Subsidy = USD0.67/L
Coconut	0.00	0.00	0.05
Cottonseed	0.00	0.09	0.05
Groundnut	0.00	0.00	0.11
Maize	0.00	0.07	0.47
Palm	86.42	66.67	57.38
Palm kernel	0.00	0.00	3.58
Rapeseed	13.58	5.42	9.77
Safflower	0.00	0.00	0.03
Soybean	0.00	17.25	15.61
Sunflower	0.00	10.50	12.95

Figure 7 shows the profitable potential biodiesel production (*PPBV*) of 12 countries at different level of subsidies. These 12 countries have potential to produce at least 500 million litres of profitable biodiesel per annum at USD0.28/L subsidy, including Indonesia, Malaysia, Argentina, Ukraine, Canada, Russian Federation, the Netherlands, Brazil, Germany, Paraguay, Papua New Guinea and Guatemala, in descending order of the potential biodiesel production. It can be seen that, as subsidy

increases from USD0.16/L to USD0.28/L, which is respectively equivalent to crude oil subsidy of USD20/bbl and USD35/bbl, these countries are able to increase the profitable potential biodiesel production by a range of 50 to 6800 million litres each year.

There are some countries that can achieve another leap in profitable potential biodiesel production with a smaller increment of subsidy, as a second feedstock becomes profitable. Argentina, Canada Germany and the Netherlands can experience a second jump in profitable production as subsidy increase from USD0.24/L to USD0.28/L. Likewise, Guatemala, Malaysia and Papua New Guinea could have a second jump when subsidy increase from USD0.43/L to USD0.51/L; and Indonesia from USD0.63/L to USD0.67/L.
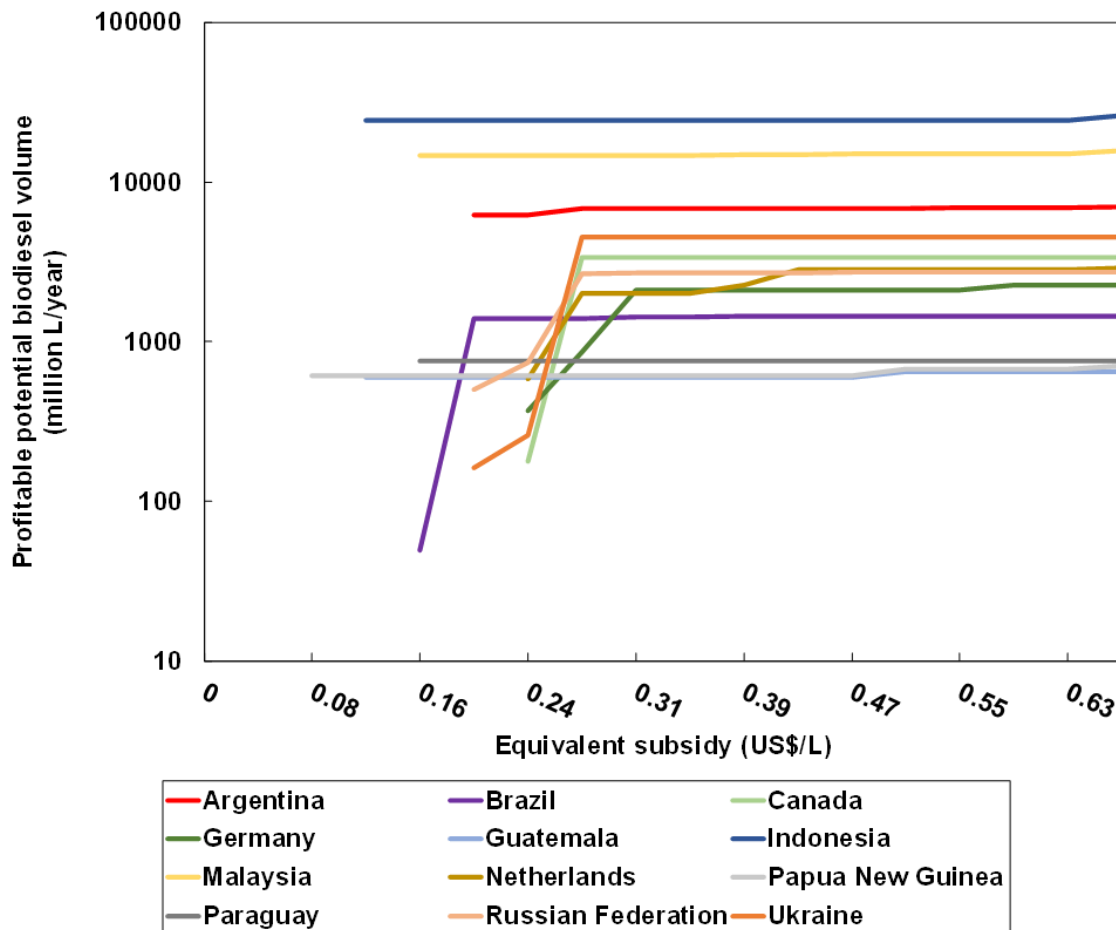

Figure 7: Profitable potential biodiesel volume that can be achieved with different subsidy for biodiesel production for the 14 countries with profitable potential biodiesel production higher than 500 million litres per annum at USD0.28/L subsidy.

4.2 Water stress

Water input is required for biodiesel production, in both feedstock production and chemical conversion process of transesterification from oil to biodiesel. Each feedstock requires different amount of water to grow the crop, as well as to extract and refine the oil. Oil is then reacted with methanol to produce biodiesel. The water required during the production of methanol is the main water consumption for the reaction.

The water required for feedstock production in each country (WR_{ij}) is calculated:

$$WR_{ij} = EQ_{ij} \times WC_i \quad \text{(Eq. 5)}$$

where WR_{ij} is the water requirement for each feedstock, EQ_{ij} the export quantity of the feedstock and WC_i the water consumption to produce the oil (Chapagain and Hoekstra, 2004; Mekonnen and Hoekstra, 2010). The water consumption includes the water used for agriculture and oil refinery.

The water used for methanol production (MWR_{gjk}) is calculated:

$$MWR_{gjk} = MW \times \frac{PPBV_{gjk}}{CR \times OMR} \quad \text{(Eq. 6)}$$

where MWR_{gjk} represents the methanol water requirement, MW the methanol water consumption and OMR the oil-methanol ratio. One tonne of methanol is produced using 20 m^3 of water on industrial scale, which is equivalent to a volumetric ratio of 15.744 m^3 of water used per m^3 of methanol produced (Romano and Sorichetti, 2011). A volumetric oil-methanol ratio of 8 is used (González *et al.*, 2007; Yang and Jackson, 2012). This is approximated using the stoichiometry of transesterification. Methanol recovery process is considered in the production, thus, the actual reactants ratio of oil and methanol is used, instead of doubling the methanol input as used in the industry. The total water required is then calculated by summing up the water requirement of all profitable feedstocks and the methanol water requirement.

The use of water in biodiesel production would introduce water stress in each country, to different levels, depending on the quantity of biodiesel produced and the water resource availability of the nation. Water stress index (WSI) is commonly used to indicate the water stress level of a region (Li *et al.*, 2017). Each industry will contribute different portion to the final water stress in a country. The fraction of water stress index ($FWSI_{gjk}$) contributed by biodiesel production is calculated:

$$FWSI_{gjk} = \frac{TWR_{gjk}}{WA_j} \qquad \text{(Eq. 7)}$$

where TWR_{gjk} is the total water requirement and WA_j is the water availability of each country, including precipitation and renewable water sources (FAO, 2014).

In order to increase the biodiesel blending ratio, certain volume of biodiesel needs to be produced according to the blending ratio to be achieved.
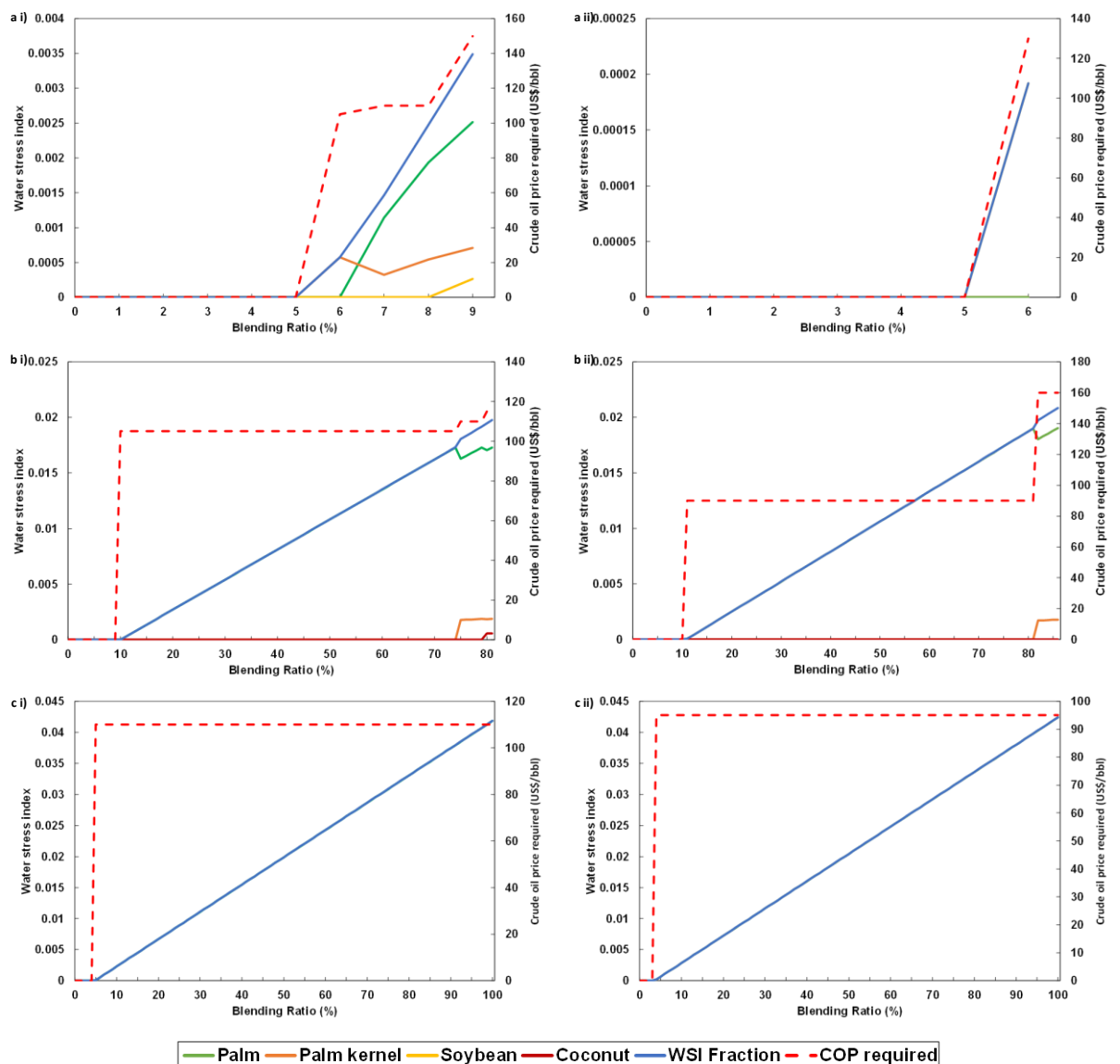
Figure 8 shows the relationship between the total *FWSI* introduced by biodiesel production and the blending ratio, as well as the *FWSI* for each feedstock used and the corresponding crude oil price required to achieve the blending ratio profitably in Thailand, Indonesia and Malaysia in 2013 and 2016. The relationship between *FWSI* and blending ratio is non-linear due to the versatility of the biodiesel production process to harness the use from various high-lipid feedstock. Each time a feedstock is added to the production, the rate of water requirement increment would change. Depending on the feedstocks available, biodiesel production increases the water stress to different extend.

Indonesia and Malaysia showed consistent trends in 2013 and 2016, while the relationship between *FWSI* and *BR* for Thailand is more linear in 2016. The change in Thailand mainly results from the variation of feedstock price and available quantity over the years. In 2013, the feedstocks in Thailand had prices at multiple levels, which led to leaps in profitable potential biodiesel production at different *COP* level, as discussed in section 4.1. However, the feedstock available is much less in Thailand in 2016 (20% of the amount as compare to that in 2013). Although Thailand can potentially achieve 6.57% blending ratio, only 6% is shown in the graph as a result of the model's resolution. At *COP* of US$140/bbl, palm will share half of the potential production and at *COP* of US$155/bbl, the production will be 48% from palm kernel, 26% from soybean and 26% from soybean. The fully extended graph for Thailand in 2016 would have similar shape as 2013 (while the proportion of each feedstock will be different).
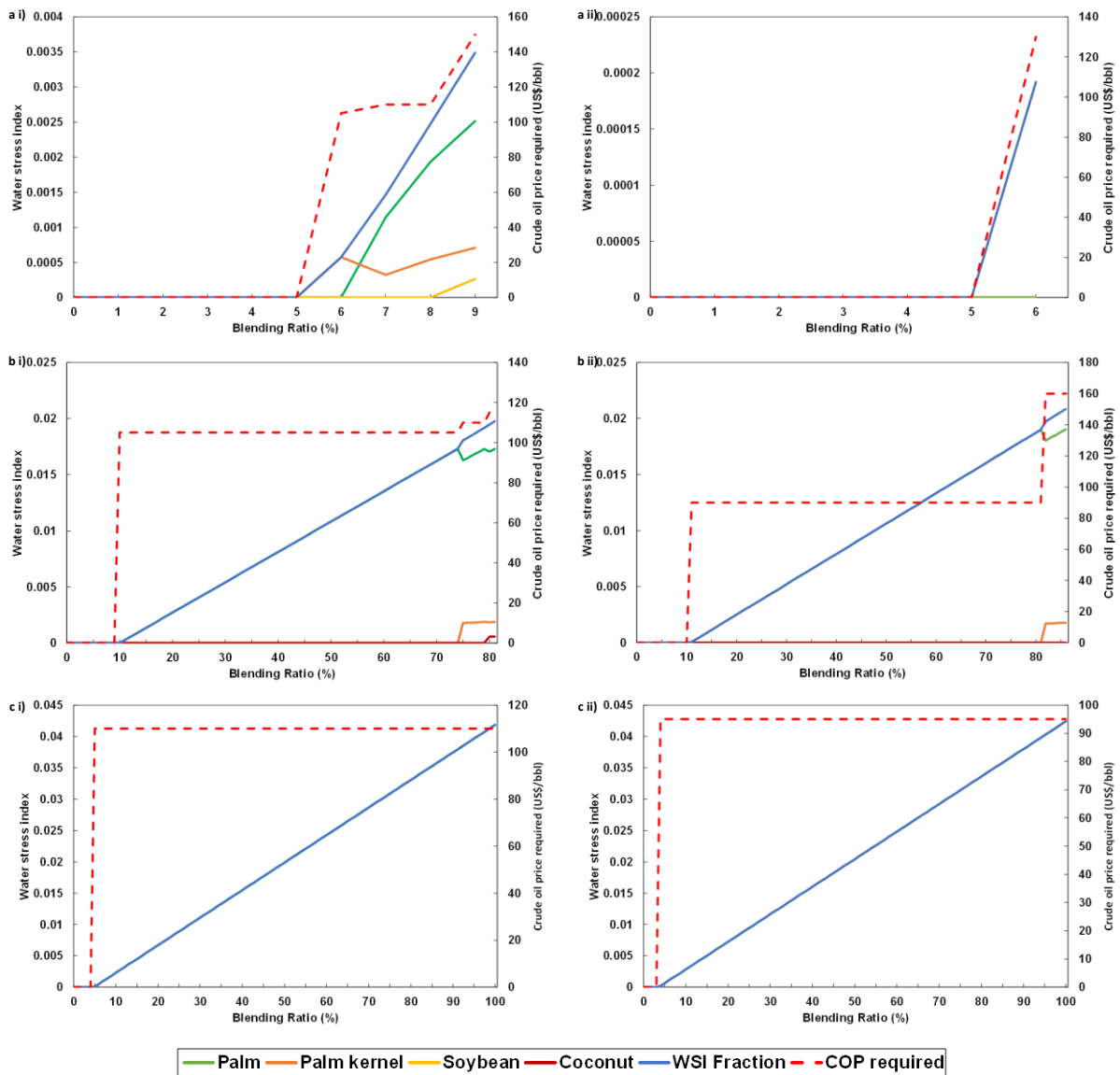
Figure 8: The total fraction of WSI contributed by biodiesel production and fraction of WSI contributed by each feedstock at each biodiesel blending ratio in a i) Thailand in 2013, a ii) Thailand in 2016, b i) Indonesia in 2013, b ii) Indonesia in 2016, c i) Malaysia in 2013 and c ii) Malaysia in 2016. The red dashed line indicates the corresponding crude oil price required to reach the blending ratio.

4.3 Food stress

The feedstocks for potential biodiesel production are considered only from the export market. The use of export-only feedstock will have the repercussions of disrupting the oil import supplies of other countries. This will invariably introduce various levels of food stress in other countries.

At current food market, most of the countries have sufficient supply in terms of average dietary energy supply adequacy (ADESA), as reported by the Committee on World Food Security (CFS) Round

Table (CFS, 2016). However, the undernourished population all over the world has dietary energy supply (DES) of 100 to 400 Cal/cap/day less than the national average dietary energy requirement (FAO, 2000). The DES of the biodiesel feedstock used in each country is calculated:

$$DES_{gjk} = \frac{TEF_{gjk}}{population_j \times 365} \qquad \text{(Eq. 8)}$$

$$TEF_{gjk} = \sum EF_{ij} \qquad \text{(Eq. 9)}$$

where *TEF* is the total energy of feedstock used for biodiesel production and *EF* is the energy contained in the feedstock of each country. A country with larger population would have higher quota for biodiesel production on an absolute quantity basis.

Figure 9 shows the dietary energy of the potential biodiesel production at different blending ratios in Thailand, Indonesia and Malaysia in 2013 and 2016. The dietary energy supply is normalised on a per capita basis. Malaysia which has the capacity to totally replace diesel fuel consumption with biodiesel will divert the highest amount of food energy into fuel as compared to regional countries like Indonesia and Thailand. The diversion might spark a food vs fuel debate, but at the same time Malaysia is also facing an increasing inventory levels of palm oil. This transforms the conversation of crude palm oil market to be not of supply shortfall, instead an oversupply issue to be tackled. The production of biodiesel will potentially absorb the oversupply of palm oil. Thus, it is best to consider the circumstances of individual countries to evaluate the food diversion issues.
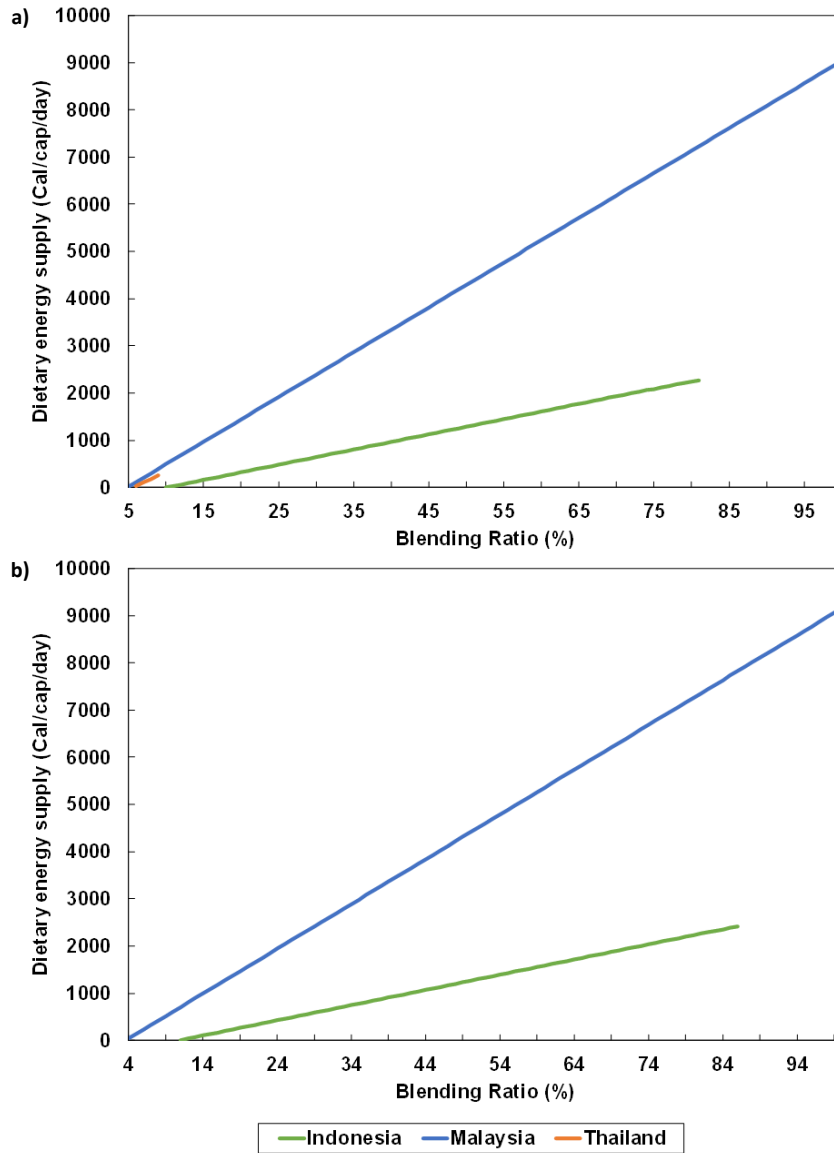
Figure 9: The dietary energy supply contained in the feedstocks used for biodiesel production in Thailand, Indonesia and Malaysia at each blending ratio in a) 2013 and b) 2016.

The percentage of population that can be fed by the feedstock is calculated in terms of fraction of *ADESA* (*FADESA*):

$$FADESA_{gjk} = \frac{TEF_{gjk}}{population_j \times 365 \times ADER_j} \qquad \text{(Eq. 10)}$$

where $ADER_j$ is the average dietary energy requirement of a country. *ADER* is calculated as a weighted average of the dietary energy requirement of each gender and age group (UNESCAP, 2013; UN, 2016). This calculation is based on the energy content of the feedstock, instead of the nutrition. Table 4 lists the percentage of population that can be fed by the feedstocks used for biodiesel production of 15

countries, at zero subsidy and at subsidies of USD0.28/L and USD0.67/L. These 15 countries include the three countries that can profitably produce biodiesel at zero subsidy and the 12 countries that can produce more than 500 million litres of profitable biodiesel at subsidy of US$0.28/L.

Table 4 Percentage of population of each country that can be fed by the profitable feedstock used for biodiesel production at zero subsidy, subsidies of USD0.28/L and USD0.67/L.

Country	Population (%)		
	Subsidy = 0	Subsidy = USD0.28/L	Subsidy = USD0.67/L
Argentina	0.00	160.77	164.06
Benin	4.48	4.48	4.48
Brazil	0.00	6.85	7.10
Canada	0.00	89.74	89.74
Germany	0.00	10.68	27.05
Guatemala	0.00	38.84	42.07
Indonesia	0.00	97.60	104.01
Ireland	2.49	2.49	2.49
Malaysia	0.00	494.97	528.30
Netherlands	0.00	122.12	173.20
Papua New Guinea	0.00	81.48	92.27
Paraguay	0.00	116.68	116.68
Russian Federation	0.00	18.85	19.24
Togo	4.77	4.77	4.77
Ukraine	0.00	102.56	102.56

4.4 Limiting factor

It is possible for all countries to replace 100% of diesel with biodiesel if there is enough feedstock. However, the environmental of the industry and security issues need to be taken into account. The production will be limited by four main factors, namely water stress, food stress, feedstock quantity and crude oil price.

Water stress is a crucial limiting factor of biodiesel production. It was reported that 8% of the global water resources is used for energy production (UNESCAP, 2013). By 2016, biofuels contribute 10% of the global primary energy (as seen in Figure 4) (IEA, 2015). A water stress index higher than 0.4 reflects high water stress (Raskin *et al.*, 1997; Vörösmarty *et al.*, 2000). With these three numbers, a maximum of 0.0032 for FWSI contributed by biodiesel production is set.

Food stress limit is set, so that if it is exceeded, there will be a possibility of increasing hunger level in countries where food sufficiency barely meets the requirement. The feedstock energy content that can provide 400 Cal/cap/day to the nation's population is set as the maximum of biodiesel production for each country. This limit can be used as an upper boundary of biodiesel production, to prevent catastrophic disruption of the global food market supply. Depending on the population of each country, the food stress limit will be different (in terms of total feedstock energy consumed).

Table 5 includes the maximum blending ratio permissible by the food stress and water stress limits for the 15 countries. The maximum blending ratio is calculated in two ways: 1) by 1% increment of blending ratio and calculate the corresponding *FWSI* and *DES*; and 2) by cumulatively taking individual feedstock one by one (in ascending order of the feedstock price) into biodiesel production and calculating the blending ratio that the country can reach, the *FWSI* and *DES*.

Table 5: Maximum blending ratio that can be achieved by the 15 countries without exceeding the food stress and water stress.

Country	Maximum blending ratio (%)	
	Food stress	Water stress
Argentina	26	30
Benin	6	6
Brazil	9	9
Canada	3	11
Germany	7	5.55
Guatemala	16	11
Indonesia	23	22
Ireland	1	1
Malaysia	7	10
Netherlands	9	7
Papua New Guinea	9	52
Paraguay	9	37
Russian Federation	6	7
Togo	9	9
Ukraine	11	4

Besides food stress and water stress, feedstock is another factor that impedes the production of biodiesel. The price and available quantity of the feedstock will both affect the industry. Feedstock price determines the production cost and the corresponding subsidy that is required for biodiesel production. The quantity of feedstock limits the maximum potential volume of biodiesel produced, hence the maximum blending ratio a country can achieve.

It has been found that, out of the 155 countries investigated, biodiesel production of 82 countries would be primarily limited by feedstock quantity, 47 limited by crude oil price, 20 by water stress and 6 by food stress. Figure 10 shows the four limiting factors (feedstock quantity, crude oil price, water stress and food stress) for each of the countries investigated. Water stress will limit biodiesel production in most of the European countries and feedstock quantity will limit the production in Africa. It is worth mentioning that, biodiesel production in Indonesia would have dual-limiting factors. In the scope of this

study, food stress would limit the biodiesel production in Indonesia to a volumetric blending ratio of 23%, and water stress would limit it to 22%.
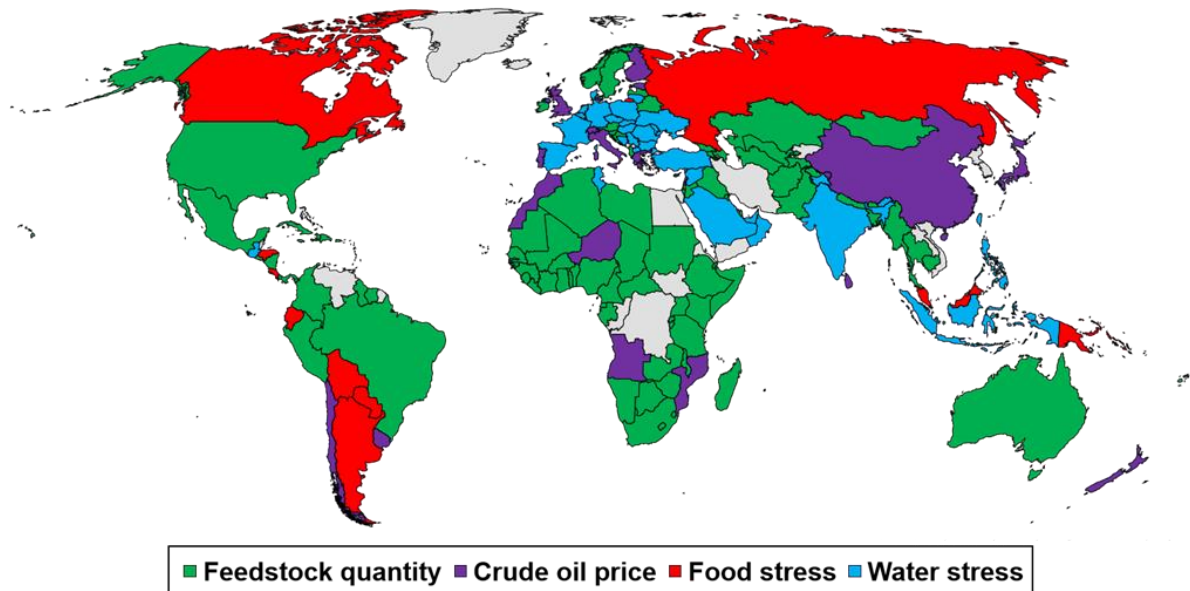

■ Feedstock quantity ■ Crude oil price ■ Food stress ■ Water stress

Figure 10: Limiting factors for biodiesel production of 155 countries.

5. Effect of biodiesel

5.1 Energy Security

The production of biodiesel will affect the energy security of a country. In this study, short-term energy security and energy diversity are measured with a modified MOSES model (IEA, 2011), and Herfindahl-Hirschman Index (HHI) (World Energy Council, 2016; Kordanuli *et al.*, 2017), respectively.

In the MOSES model, the short-term energy security of each country is evaluated with three parameters, including import dependence, entry points and volatility of agricultural output. These parameters represent the external risk, external resilience and domestic risk of biofuel industry, in that order. Each country is given a grade of A, B or C, which respectively indicates low, medium and high risk of the industry. The risk refers to the possible short-term disruptions that the energy system could experience and the capability of the system to recover from the disruptions.

For the 45 countries with complete dataset, the short-term energy security was evaluated with potential biodiesel production. Figure 11 shows the short-term energy security grading of biodiesel industry with and without the addition of potential biodiesel production in 2013 and 2016. It can be seen that, out of the 45 countries, five countries have potential to improve the short-term energy security from grade C to B, and one country from B to A. These improvements generally occur in East Asian and European countries. With the addition of potential biodiesel, the biodiesel industry of these countries would be more invulnerable to short-term disruption.
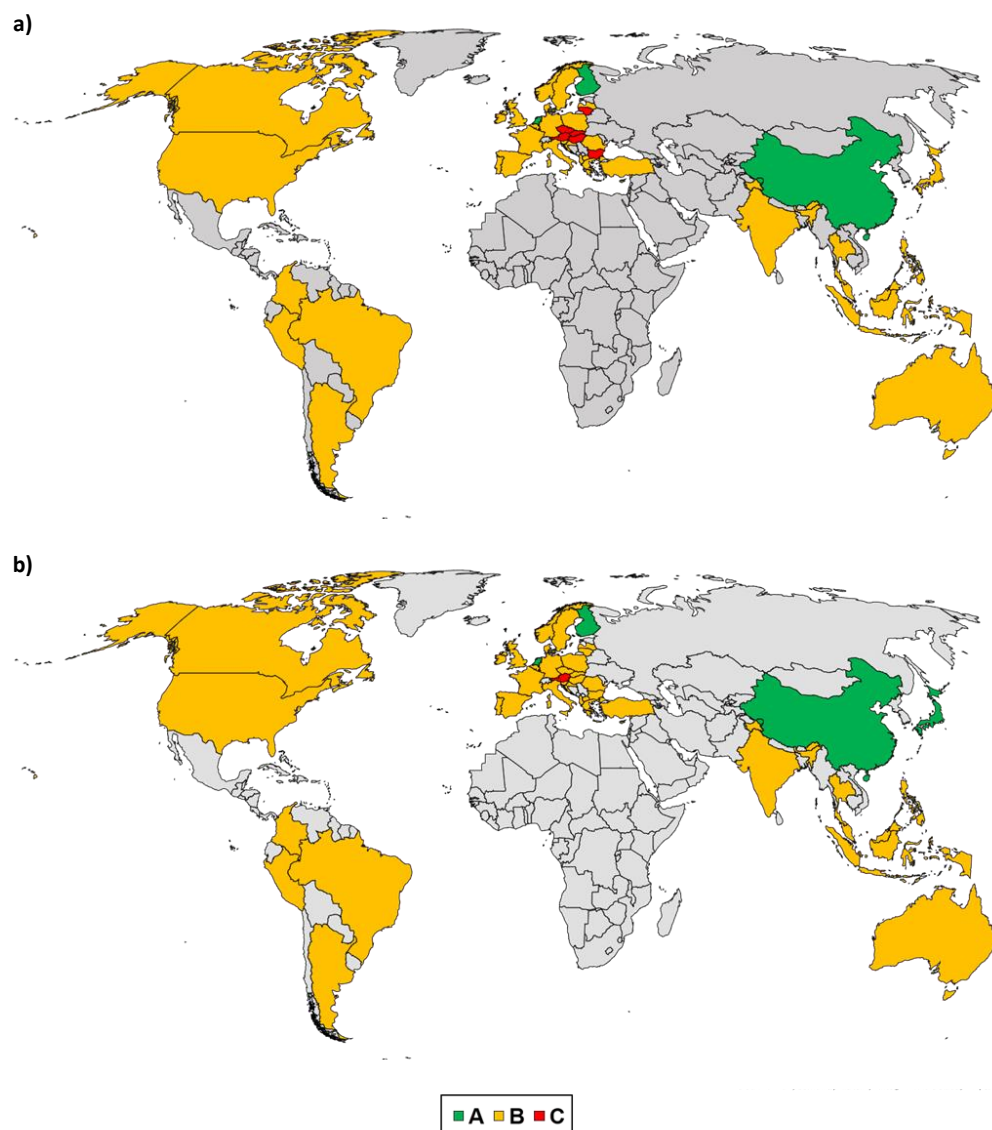

Figure 11: Biodiesel industry short-term energy security category of countries a) at current biodiesel production and b) with potential biodiesel production.

Addition of biodiesel production will also alter the energy diversity. The diversity of a country's primary energy is measured with the Herfindahl-Hirschman Index (HHI):

$$HHI_{gjk} = \sum ES^2 \qquad \text{(Eq. 11)}$$

where *ES* is the primary energy source, as a percentage of total primary energy of each country, including coal, crude oil, oil products, natural gas, nuclear, hydro, geothermal and solar, and biofuels and waste. Lower HHI represents broader energy diversity. The energy of potential biodiesel production is added into biofuels and waste. Depending on the primary energy profile of each country, the energy diversity can potentially be improved or worsen. Figure 12 shows the HHI change with biodiesel blending ratio in Thailand, Indonesia and Malaysia.

Of the 84 countries with potential biodiesel feedstock investigated, 53 could broaden their energy diversity with potential biodiesel production. These include both developing and developed countries in all continents (UNSTATS, 2006). On the other hand, 23 countries would be reducing the energy diversity, including 12 countries located around the equatorial belt, as well as 11 European countries. The former group of countries have abundant biodiesel feedstock sources, such as palm and soybean. The European countries, including Germany and Italy, have already been promoting biodiesel as a greener, renewable alternative to diesel (Naylor and Higgins, 2017). These 25 countries were found to have a high usage of biofuel (25% to 99% of total primary energy), that the energy diversity would decrease with addition of potential biodiesel production.
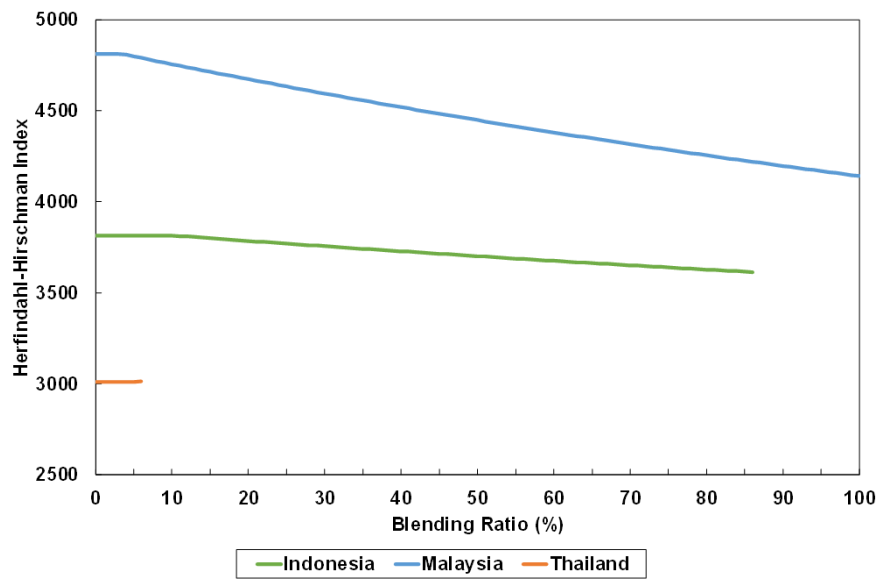
Figure 12: The HHI at each blending ratio achievable in Thailand, Indonesia and Malaysia.

5.2 Emission

Biodiesel is intended to be used as a cleaner alternative fuel to replace diesel. The emission properties of biodiesel differ from those of diesel, due to different chemical and physical properties. The NO, CO, unburned hydrocarbon (UHC) and smoke emission of biodiesel from each feedstock are compared with the emissions from diesel. The emissions were calculated using the fuel properties (Table 2) and the emissions predictor equation. Table 6 shows the predictor equations used to calculate each type of the emissions (Ng, Ng and Gan, 2012).

Table *7* shows the percentage difference of the four emissions from each biodiesel feedstock as compared to diesel emissions. All biodiesel, besides olive and rice bran biodiesel, show reduction in smoke opacity (by more than 20%). Coconut biodiesel has reductions in all four types of emissions. Coconut biodiesel has high cetane number and oxygen content, and low kinematic viscosity and carbon residue. These properties make coconut biodiesel the cleanest first-generation biodiesel for use in the transportation sector. It has the most emission reduction in CO, UHC and smoke opacity, and the second most reduction in NO emission.

Table 6: The emission predictor equation coefficients of NO, CO, UHC and smoke opacity for the corresponding fuel property.

Type of emission	Unit	Cetane number	Kinematic viscosity (mm2/s)	Fuel density (kg/m3)	Carbon residue (%)	Oxygen content (%)	Constant
NO	ppm by vol	-1.8415		+0.0251		-0.0580	+402
CO	%	-1.30E-04	+5.83E-04	+1.04E-05	-5.20E-04		+0.0253
UHC	ppm by vol	-0.0162	+0.3154	-0.00015	+1.4146	-0.0197	+3.1818
Smoke opacity	%	+0.0182	+0.1944		+13.7769	-0.1015	+2.6283

Table 7: Percentage change in NO, CO, UHC and smoke emission of each biodiesel as compared to baseline diesel emissions.

Feedstock	NO (%)	CO (%)	UHC (%)	Smoke opacity (%)
Coconuts	-0.45	-0.90	-22.77	-51.98
Cottonseed	7.30	9.50	5.71	-37.98
Groundnut	6.36	8.92	8.61	-21.16
Kapok	4.91	7.38	3.38	-34.82
Maize	7.81	9.07	5.42	-23.55
Olives	3.92	7.31	15.02	11.98
Palm	-1.39	2.00	-4.60	-35.91
Palm kernels	5.24	3.52	-12.49	-31.44
Rapeseed	6.84	9.12	4.35	-39.85
Rice bran	5.49	7.77	13.33	12.22
Safflower	8.25	9.00	3.69	-24.37
Sesame	8.92	9.30	3.30	-35.70
Soybean	8.74	9.36	-0.76	-45.14
Sunflower	8.18	9.89	6.17	-31.60

The possible emission changes by partially replacing diesel with the profitable potential biodiesel can be calculated. Figure 13 shows the emission changes by replacing diesel with profitable potential biodiesel at a subsidy of USD0.67/L in 12 countries. Smoke opacity will be reduced with the highest percentage in all countries with potential biodiesel production (nearly 50% in Malaysia and over 30% in Argentina and Indonesia). UHC and NO emissions can be reduced in countries where coconut and/or palm biodiesel are dominant, such as Indonesia, Malaysia Papua New Guinea and Guatemala. UHC emission can also be reduced in countries with palm kernel as dominant feedstock of biodiesel, such as Thailand.
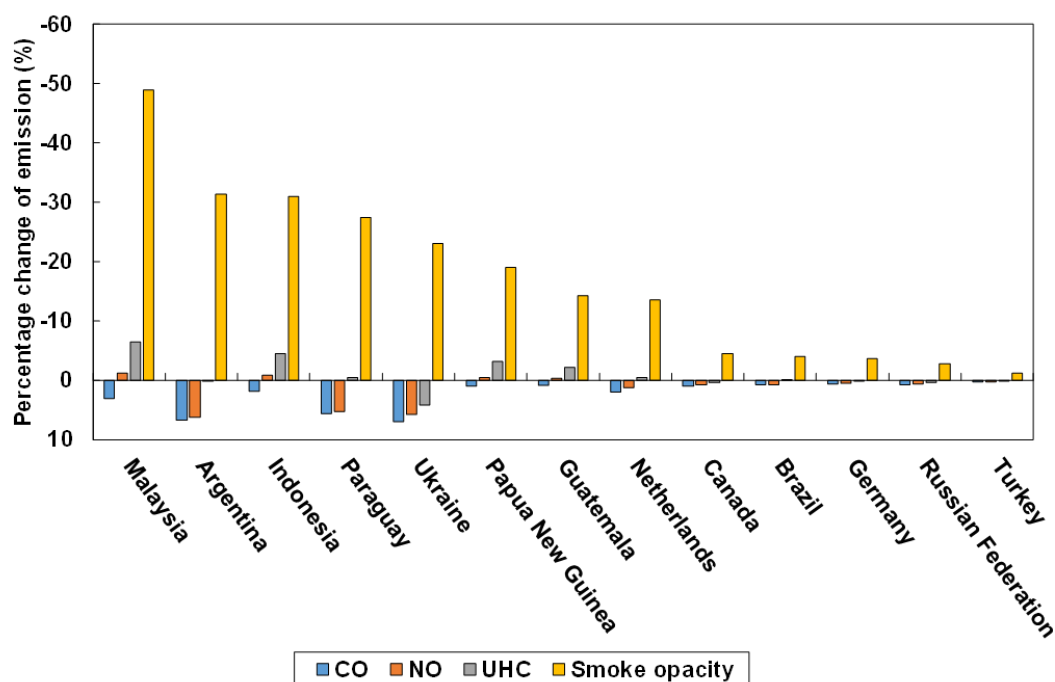
Figure 13: The percentage change of emission by replacing diesel with profitable potential biodiesel at subsidy of USD0.67/L.

Conclusions

This study focuses on the sustainability of biodiesel production in the energy-water-food (EWF) nexus, as well as the global impact of biodiesel as a renewable alternative fuel to diesel. The result shows that, with the potential first-generation biodiesel feedstocks, the renewable energy proportion in the global primary energy mix can increase by 0.43%. Yet, biodiesel industry in most of the countries will be profitable only if there is governmental intervention in the form of subsidies. At a subsidy level of USD0.67/L, among the 84 countries with potential biodiesel feedstocks, 53 could broaden their energy diversity and 23 could be reducing the energy source variety. In terms of resource management from an EWF nexus perspective, the limiting factors curtailing biodiesel production in 82, 47, 20 and 6 countries are relating to the aspects of feedstock quantity, crude oil price, water stress and food stress, respectively. The major factor limiting the potential biodiesel production in Africa will be feedstock quantity, and water stress will be impeding the production in most of the European countries. It can be said that, feedstock quantity and crude oil price will be the factors that limit biodiesel production, and

the biodiesel sustainability will be primarily impeded by water stress. The result of this study can serve as a guideline for governments to consider the feasibility and sustainability of biodiesel industry.

Acknowledgement

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