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Review

Feasibility of microalgae as feedstock for alternative fuel in Malaysia: A review

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ABSTRACT

Biodiesel is an attractive fuel replacement for diesel engine in Malaysia. The application of biodiesel as fuel-blend has been implemented commercially in transport sector in the country. Among various potential feedstock for biodiesel production, microalgae have been appeared as a promising source since a decade due to its' high biomass productivity, rapid growth rate, large amount of lipid content, capability of high CO_2 capture and sequestration as well as suitable geographical location to be harvested. The main objective of this study was to determine the feasibility of microalgae harvesting in Malaysia to produce biodiesel and potential to implement microalgae-biodiesel as commercial transportation fuel. This study demonstrated the current scenario of overall biodiesel production and application in Malaysia. Since Malaysia is the world's second-largest oil palm producer, exploitation of edible palm oil for the making of biodiesel is to be blamed as the cause of soaring food price; therefore, the country is currently looking for 3rd generation biofuel sources and microalgae has been preferred for this purpose. Therefore, insight of the significance of microalgae cultivation for this purpose, suitable microalgae candidates and possible feasibility of microalgae biodiesel have been delineated in this review study. Prospects and challenges to implement microalgae biodiesel have also been emphasized in this study. Therefore, the advantages and limitations of this biodiesel can be transparent to government and non-government sectors. Thus, this study can re-direct both sectors in future. Consequently, it may contribute setting an appropriate government policy to encourage microalgae for biodiesel production to sustain the local biofuel and secure economic growth, energy security and improve environmental conditions in near future.

1. Introduction

Energy is crucial for all living beings, especially humans. For decades, non-renewable energy sources i.e. coal, gas and petroleum have been exploited and diminishing continuously to support daily human activity [1–3]. After the global energy crisis of the 1970s, energy security has become very critical to ensuring the country's economic growth. In July 2008, petroleum price reached US$ 174 per barrel, the highest in history due to continuous depletion of the resources [4]. However, oil remains the world's dominant fuel as the main source of energy demand, accounting for 33.6% of the total global share [5]. For this purpose, researchers are seeking the best possible use of renewables such as solar, hydro, ocean, geothermal, wind and bioenergy [6–17].

Fossil fuel depletion, which is closely associated with environmental degradation is predicted to become the biggest problem in the future. Concerned with the problems, there is a need to increase energy security and reduce greenhouse gas (GHG) emissions [18–23]. Burning fossil fuel generates GHGs emission and other types of air pollutants that can harm the ecosystem. These problems are key drivers in the research for renewable fuel alternatives [24–27]. One of the most promising alternatives is to substitute fossil fuel based diesel oil with biodiesel [28].

Biodiesel is derived from long-fatty acid triglyceride in the form of mono-alkyl esters as shown in Reaction 1, which undergoes transesterification or esterification in the presence of alcohol (methanol) [29–34].

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Table 1
Technical and environmental advantages of biodiesel [49].

Description	Advantages
Cetane number/Diesel Improver	52.4 c.f 37.7 for petroleum diesel from Europe
Engine oil	Still useable after recommended mileage.
Exhaust gas emission	Much cleaner (reduction of hydrocarbon, CO, CO_2, SO_2 content).
Knocking	No
Modification of conventional diesel engine	Not required
Performance of engine	Good
Running	Smooth
Starting	Easy

$$CH_2COOR^1 - CHCOOR^2 - CH_2COOR^3(Triglyceride) + 3CH_3OH(Methanol) \overset{KOH}{\longleftrightarrow} CH_2OH - CHOH - CH_2OH(Glycerol) + CH_3COOR^1 - CH_3COOR^2 - CH_3COOR^3(Biodiesel) \tag{Rc.1}$$

Biodiesel typically has similar characteristics to petrodiesel in terms of viscosity, energy content, cetane number, and phase changes. Due to this similarity, it can be easily blended together with petrodiesel to be used in conventional diesel engines without further requirement of modification [35–41]. The advantage of using biodiesel compared to petro-diesel includes reduced greenhouse gas emissions, increased lubricity and cetane ignition [42–50]. The technical and environmental benefits offered by biodiesel are presented in Table 1 [51].

Based on the report of biodiesel production from the International Energy Agency (IEA), global biodiesel production has risen sharply over the last few years. Between 2000 until 2011, biodiesel production grew from 806 to 21400 million liters while in 2020, total biodiesel production peaked at approximately 80000 million liters. The world's biodiesel production from 1991 to 2020 is presented in Fig. 1 [52–55].

A great advantage of microalgae biodiesel compared to biodiesel from first generation biodiesel is enhanced physical properties that causes better combustion quality in diesel engines. Previous experimental studies demonstrated that biodiesel from microalgae species e.g. *Spirulina platensis, Chlorella protothecoides* and others presented much higher density, viscosity, initial boiling point, total acid number, cetane number, flash point, calorific value, and diesel index compared to biodiesel from first generation feedstocks such coconut, palm and soybean biodiesel in Malaysia. Along with enhancing these parameters, microalgae biodiesel also contained lower ash and water content, sulfur and carbon residue, pour point and cloud point which manifested microalgae biodiesel more feasible than other biodiesel for fuel quality purpose [56–59].

The main goal of this research was to present current scenario of biodiesel in Malaysia, present the possibility of the initiation of microalgae biodiesel in the country and demonstrate a comparative biodiesel study between microalgae and oil palm-based biodiesel since oil palm is the most dominated feedstock for biodiesel production in the country. Many experimental studies on biodiesel production various biomass have been demonstrated in Malaysia while microalgae are still being a new feedstock for biodiesel in the country. Mostly previous review studies on microalgal biodiesel in Malaysia descried on the experimental techniques, variation of biomass yield based different strains, various growth factors and others [60,61]. The research gap of this current review study to demonstrate the comparative scenario of biodiesel production from microalgae and other feedstock such as palm oil, jatropha oil and others. The significance of this study is to present possible fuel market perspective of microalgae biodiesel while oil palm can be one of the most dominant sources.

2. Current scenario of biodiesel application in Malaysia

Global palm oil production has grown significantly since the 1970s and has dominated the vegetable oil market worldwide. Consequently, in the last twenty years, palm oil has doubled its share [62–64]. Recognizing the potential revenue of palm oil based biodiesel in the global market, Malaysian government developed ambitious biofuel policies, thereby creating a new export industry and increases local energy security [65]. In addition, attempts are being made to produce biodiesel in massive scale without considering the environmental effects such as deforestation and biodiversity extinction [66].

In the early 1870s, oil palm tree (*Elaeis guineensis*) was introduced in the Malaysia [67]. With seed imported from Indonesia, the first commercial plantation took place in Tennamaran in 1917. After 1960, the Government of Malaysia saw the prospect of palm oil and boosted the expansion of palm oil plantation, although at that time it was not originally intended for the production of biodiesel. The timeline of the development of Malaysian palm oil is presented in Table 2 [66].

In the early 1980s, the Malaysian Palm Oil Board (MPOB) had carried out many aggressive stances after the government realized the standing of biodiesel development in the long term. Extensive laboratory researches followed by field trials were conducted repeatedly without any major breakthrough. This condition was due to inconsistent political support and weak industrial demand [68]. However, right after the government introduced the "Fifth Fuel Policy" under the "Eighth Malaysian Plan (2001–2005)" and intensive collaboration with foreign investments, Malaysian biodiesel industry experienced a vibrant growth [68]. The growth of world's oil palm industry has been phenomenal with the largest share in Indonesia and Malaysia respectively. The acceleration programs to boost oil palm plantation in Malaysia result in significant expansion of palm oil plantation area and growth of palm oil production in Malaysia as shown in Fig. 2 and Fig. 3 [65,69].

Due to the violent swing of palm oil prices, jatropha has taken many attentions as alternative feedstock. More research is required before it can be cultivated in a large scale. The plantation organizations are tasked by the government to realize this plan. While the Malaysian Rubber Board is assigned to carry out seed breeding, National Tobacco Board is assigned to investigate the suitability of jatropha to be planted in brisk soil in the northern part of the country. Furthermore, the Malaysian Palm Oil Board was assigned the task to carry out biodiesel testing from jatropha [70]. An experimental study presented that, jatropha oil contained maximum mono-unsaturated fatty acid (45.4%), the main component for biodiesel production compared to other popular biodiesel feedstock in Malaysia such as palm oil (39.2%), soybean oil (23.4%) and sunflower oil (21.1%) [71].

Biodiesel has been acknowledged as the prospective petrodiesel replacement by the world society and have received financial and policy supports thus benefiting the society and the environment. Malaysia's key drivers in its development of the biodiesel industry are the potential to increase employment rate, boost export earnings, enhance energy security and raise the country's income besides its potential in reducing GHGs emission. Although palm oil industries are a powerful instrument

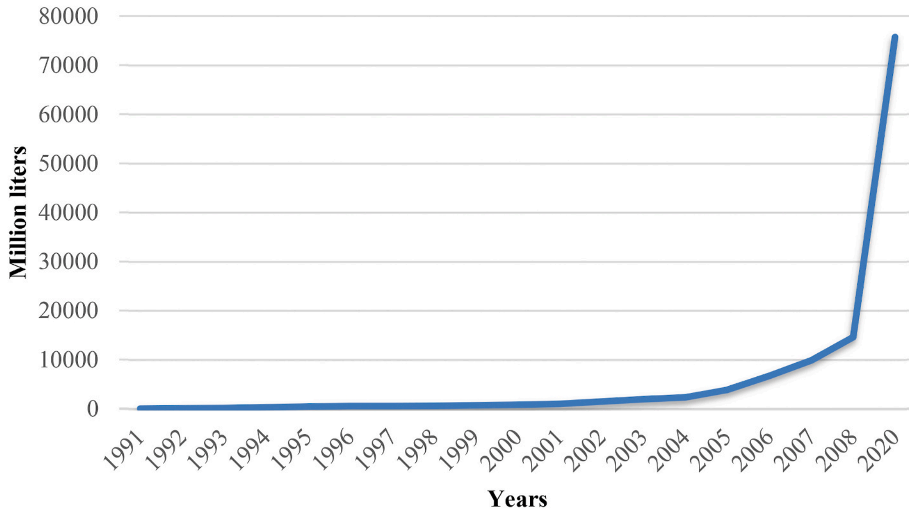

Fig. 1. Current scenario of biodiesel production worldwide [52,53,55].

Table 2
Development of palm oil industry from 1870 in Malaysia [56].

Year	Description
1870 to 1917	Experiment and ornamental planting
1917 to 1960	Private individual estates (Colonial)
1960 to 1979	Aggressive commercial cultivation and export
1979 to 1986	Integrating the processing of palm oil
	Commencement of the expansion of plantation areas in Peninsular Malaysia and Sabah.
1986 to 1996	Export market expansion; production diversification and establishment of oleo chemical industry
	Further Expansion of plantation areas in Peninsular Malaysia and Sabah
1996 to present	Product diversification and value adding
	The expansion of plantation areas in Eastern Malaysia and Indonesia

for the country's development, it is also associated with the exploitation of labor, deforestation, pollution from forest burning and dispossession of land from indigenous communities [66]. Consideration of these factors leads to the identification of microalgae as the next potential feedstock for biodiesel. High lipid content, rapid growth rate and high CO_2 fixation are some of the advantages offered by microalgae [72]. This study provided a critical analysis and review in considering microalgae as commercial feedstock for biodiesel production and the suitability to harvest in Malaysia.

3. Microalgae for biodiesel

Microalgae can be referred as photosynthetic organisms which grow in aquatic environments in both marine and freshwater [73]. They have a similar mechanism with terrestrial plant photosynthesis, however, due to the simple cell structure and a large surface-to-volume-body ratio with the fact that they are submerged in an aqueous environment, the mechanism is efficient by taking large amount of water, CO_2, and other nutrients, and converting them into biomass [74]. Microalgae can be classified based on their basic cellular structure, life cycle, and pigmentation [75]. However, biologists categorized them into three important classes in terms of abundance, namely [76]:

- the green microalgae (*Chlorophyceae*),
- the diatoms (*Bacillariophyceae*), and
- the golden microalgae (*Chrysophyceae*).

The main drivers to the shift towards microalgae are its higher oil productivity (i.e. able to produce greater oil yield at small ecological footprint) as compared to conventional biofuel feedstocks. They are

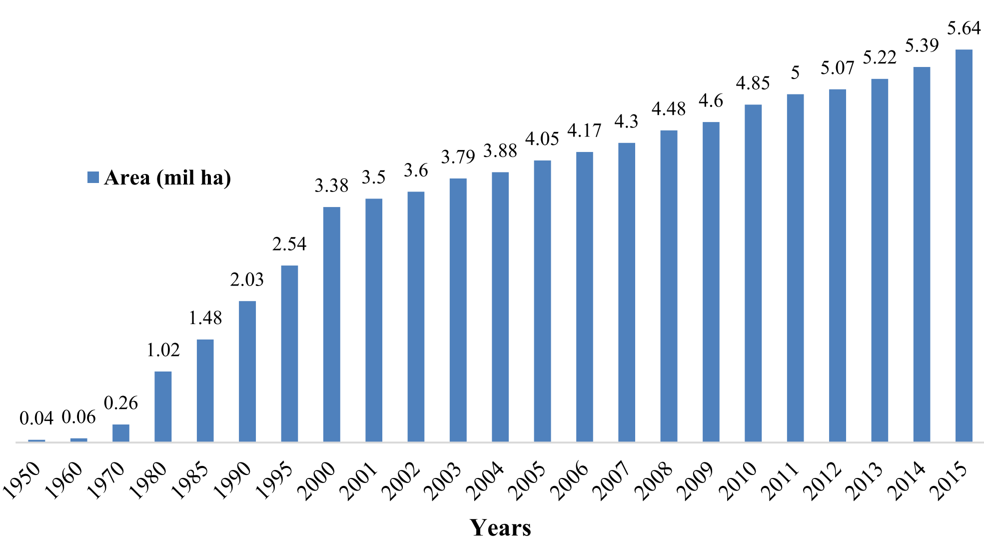

Fig. 2. Total palm oil plantation area in Malaysia [65,69].

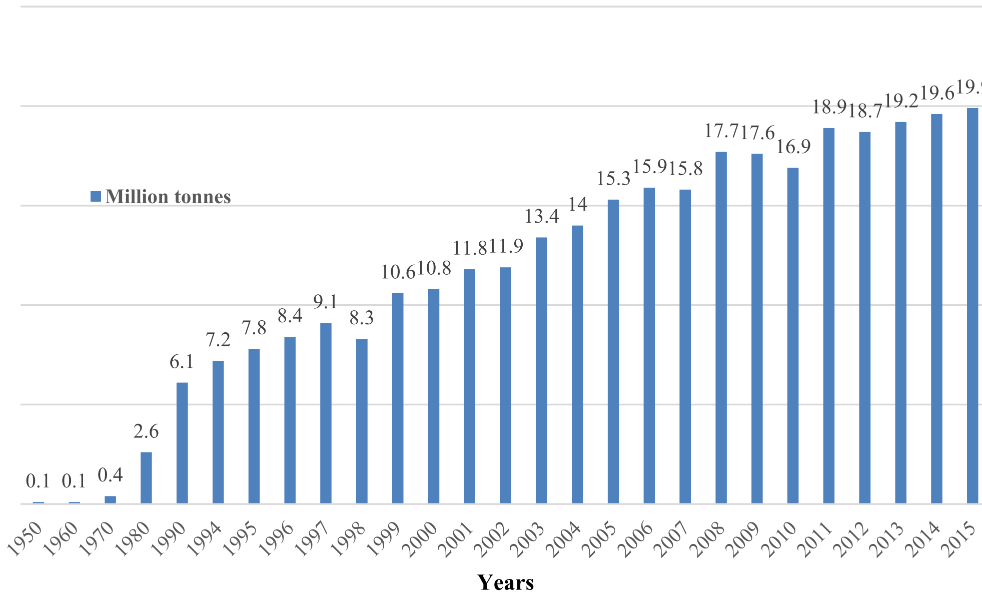

Fig. 3. Continuous growth of palm oil production in Malaysia [65,69].

Table 3
Potential microalgae species suitable for Malaysian weather and yield of oil content (%) [64,66].

Microalgae	Yield of oil content (% dry wt.)
Monallanthussalina N	20
Cylindrotheca spp.	16–37
Nannochloropsis spp.	31–68
Phaeodactylum tricornulum	20–30
Dunaliella primolecta	23
Botryococcus braunii	25–27
Chlorella spp.	28–32
Schizochytrium spp.	50–77
Neochloris oleoabundans	35–54
Nannochloris spp.	20–35
Crypthecodinium cohnii	20
Tetraselmis sueica	15–23
Isochysis spp.	25–33
Nitzschia spp.	45–47

known to double its biomass within 24 h or as short as 3.5 h and contains high lipid content, commonly about 20%–50% oil content by weight of dry mass [77]. The oil content of several selected microalgae is presented in Table 3 [75,77]. Additionally, cultivation of microalgae can potentially be coupled with carbon sequestration and wastewater treatment such that they can absorb CO_2, nitrates, and phosphates while releasing oxygen and water [68]. Microalgae biomass can also be processed such that it could produce valuable co-products which can be valuable for food, chemicals, and feed ingredients industry [78].

4. Feasibility of using microalgae as biodiesel feedstock

A sustainable biofuel needs to be one that results in a net decrease in greenhouse gas emissions, does not have any hindering effect to the local environment in its implementation, is priced competitively with existing fuel resources, able to provide for employment opportunities locally and does not compete land usage with food crops [78–86]. An experimental study on biodiesel from microalgae presented that *Chlorella* species contained very high content of fatty acid and 34.53–230.38 mg $L^{-1}d^{-1}$ biodiesel was produced from these *Chlorella* strains in Malaysia [87]. Besides, microalgae contain zero lignin and its third-generation biofuel feedstock, the huge delignification cost can be saved to produce biodiesel from this feedstock. Its significant to noted that first generation feedstock (such as soybean oil, sunflower oil, palm oil and others) has lost popularity for biodiesel due to food and feed chain disruption and second-generation feedstock (such as jatropha oil, swiss grass, woody biomass, waste biomass and others) are fading popularity for biodiesel due to the high pre-treatment cost of delignification and chemical processing. Therefore, microalgae harvesting for biodiesel can save large investment for pre-treatment and chemical processing in wood industries [88,89]. So far, microalgae have already shown its potential in replacing palm oil as a source of renewable energy production. However, growing microalgae for this purpose requires extensive research in order that the most economical and environmentally processing route can be commercialized [91]. Subsequently, the study of proper conditions for growing microalgae is equally essential.

4.1. Geography and growing conditions

Malaysia's weather condition and its location in tropical region bring beneficial features in terms of microalgae biodiesel production, specifically in the ease to grow microalgae. Here, conditions including CO_2 supply, light, nutrient, and temperature are discussed.

Since microalgae are photosynthetic microorganisms, CO_2 is essential for growth. Air in its natural form consists only 0.0383% of CO_2, the amount is not appropriate to mass culture microalgae, as they need vast amounts of air bubbling to meet the required CO_2. Other possibilities are the use of pure CO_2, which is rather expensive, of flue gas from power generation and of industries which contain a high concentration of CO_2 [91].

Most of Malaysia's electricity generation comes from fossil fuel resources such as coal and natural gas, which its combustion results in CO_2 production. Using CO_2 emitted from these plants can then 1) provide sufficient CO_2 supply for mass cultivation of microalgae based biodiesel, and 2) sequester CO_2 emission to the atmosphere, therefore, allowing Malaysia to abide to the Kyoto Protocol [68]. Malaysia consumes about 56,000 tons of coal everyday through its seven coal-fired power plants. For a typical coal fired power plant, close to three tons of CO_2 are emitted for every tons of coal. Based on the data provided by "Index Mundi", Malaysia produces 180 million metric tons of CO_2 of which 50% coming from electricity generation and industrial processes. This is mostly through the use of fossil fuels like coal, gas and fossil fuel [92]. Malaysian CO_2 emission and the share in terms of their source from 1971 until 2014 is presented in Fig. 4 and Fig. 5 [93], in which data for the years 2011–2014 was prediction values.

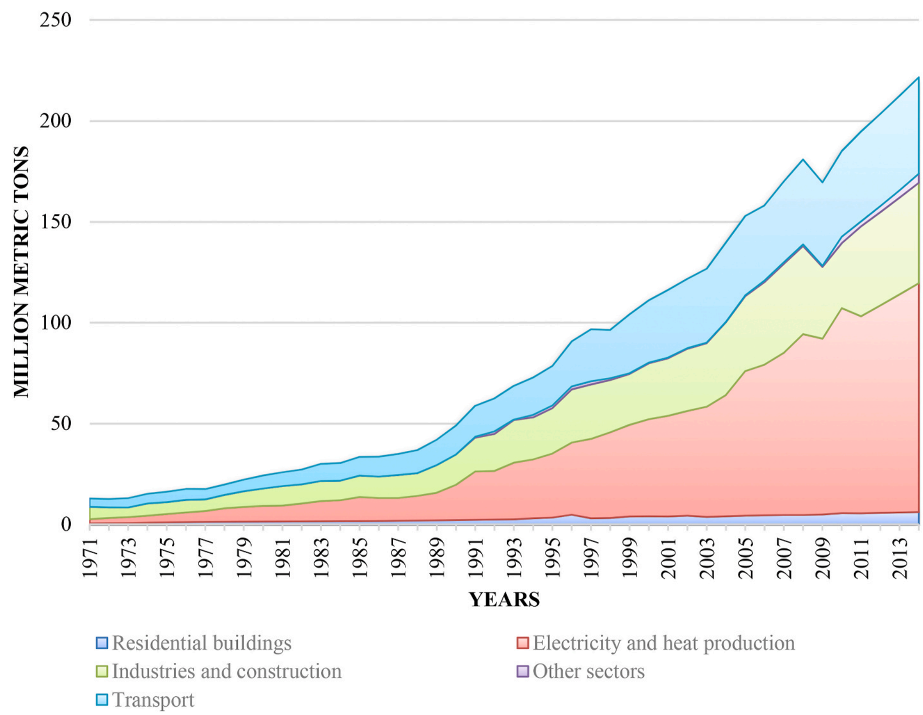

Fig. 4. Average CO_2 emission profile from different sources in Malaysia [93].

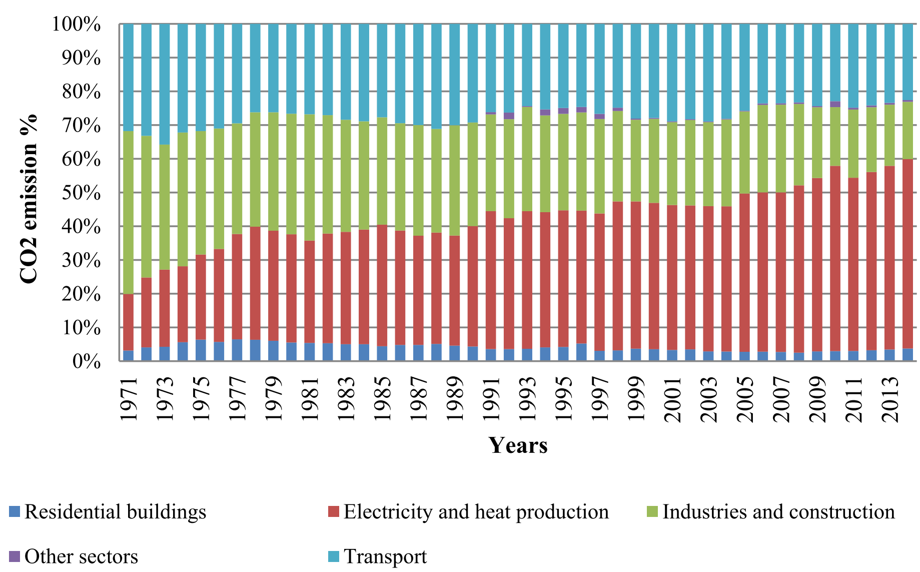

Fig. 5. Average CO_2 share from various sectors in Malaysia [93].

The flue gas from power generation can be used to feed microalgae, however, besides CO_2, flue gas also consists of several components such as NO_X and SO_X. There is not much difference in microalgae growth after feeding with pure CO_2 and flue gas from power plant consisting of CO_2, $SO_2$and NO_X. In addition, NO_X in the flue gas can be used by microalgae as the nitrogen source [94]. Recently, it has been confirmed that flue gas can be used to grow microalgae without harmful effects [91].

Light is the one of the most important elements in microalgae growth. The source of light may be natural or supplied by fluorescent tubes [95–98]. The microalgae use light to carry out photosynthesis process. However, only 40% is photosynthetically active radiation (PAR, ~400–700 nm) and up to 60% of radiation absorbed is wasted as heat [91]. Photosynthetic process does not occur at night, thus microalgae consumes up to 25% of the biomass that have been produced during the day for respiration [99].

Light is available at different geological location in different quantities [100]. Malaysia is located in the zone with the highest annual solar irradiances and it provides an uninterrupted and well distributed light to support the continuity of the photosynthesis process. This condition makes Malaysia as one of the most strategic place for microalgae growth to be further utilized in biodiesel production.

Besides CO_2 and light, microalgae require nitrogen (N) and phosphorus (P) for photosynthesis process and growth. These nutrients can be obtained from typical agricultural fertilizers at additional cost [101,102]. A cheaper option would be to use wastewater from fishery, piggery and palm oil effluent to obtain the needed nutrients [103,104].

The combination of light, CO_2, and nutrients during the photosynthesis process results in chlorophyll production. Chlorophyll concentrations are measured by satellite because of its reflection of green light, which is a good indication of the best geographic locations for (unfertilized) microalgae growth. Malaysia has been one of the most viable geographical regions for high chlorophyll concentration in the global map of chlorophyll distribution [91]. Geographic Information Systems (GIS) is the system for capturing and displaying data related to a position on the earth's surface. with the help of GIS, the coastal area (between 0 and 25 km from the coast) of Malaysia presented 5 mg/m^3 chlorophyll [91].

According to the chlorophyll distribution report, most of the green regions are located around Malaysia and Indonesia, which increases the potential of microalgae-based biomass production from these countries. Unlike microalgae that grow in mild and subtropical regions, the microalgae in tropical region grow throughout the year. Generally, temperatures lower than 15°C will slow down the growth of this species, whereas high temperature over 35°C is lethal for some species. Most of microalgae species tolerate temperatures between 15°C to 27°C. The location of Malaysia is reported to be beneficial geographically due to the suitable consistent temperature for microalgae growth throughout the year [105].

4.2. Available land area

The available land area in Malaysia is more than 32.98 million hectares, in which about 24.31 million hectares of the land are covered by trees. From this figure, only 24.9% of total forested area is used for cropping rubber, oil palm, cocoa, and coconut. The rest of which approximately about 18.25 million hectares are used for wood production, national parks and permanent reserved forest [106]. The share of the land use area in Malaysia is presented in Table 4 [106].

The robust nature and rapid growth rate of microalgae allows its mass cultivation in non-arable land area, therefore eliminating competition with land used for food crops. In Malaysia, potential sites for mass cultivation of microalgae are coastline areas and under-utilized rice land [68]. These marginal lands are unproductive due to saltwater infiltration and thus can be used to cultivate marine microalgae, which are suitable with salt water [107,108].

5. Prospects and challenges of microalgae based biodiesel in Malaysia

While it is feasible to carry out mass cultivation of microalgae based biodiesel in Malaysia, some potential prospects and challenges are recognized and elaborated further below.

Fig. 6 shows the comparison in terms of consumption between petrodiesel and biodiesel in Malaysia from 1980 until 2013 [109]. This figure shows that biodiesel consumption in Malaysia is only a small portion (2% of total petrodiesel consumption) indicating a vast potential for total petrodiesel replacement with biodiesel. Additionally, with the full implementation of B5 mandate by the Malaysian government in 2014, 359 million liters of crude palm oil based biodiesel are consumed with 73.25% of total consumption goes to local consumption [110]. The Malaysian government has plans for increasing the biodiesel composition in current diesel blends to be 7%, 10% and ultimately 15% by 2020 as a step to reduce dependency on petrodiesel [110]. In order to meet

Table 4
Overall state-based scenario of cropland in Malaysia [91].

Region	Land Area	Forested Area	Other Tree Crops	Total Area covered by tree	% of Tree Cover
Peninsular	13.18	5.89	3.57	9.46	71.8
Sabah	7.48	4.30	1.46	5.76	77.0
Sarawak	12.32	8.06	1.03	9.09	73.8
Malaysia	32.98	18.25	6.06	24.31	73.7

*In million hectares.

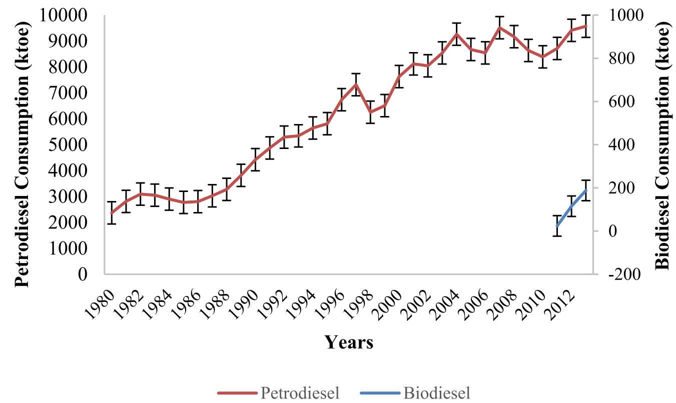

Fig. 6. Total energy consumption by petrodiesel and biodiesel in fuel market (ktoe) [109].

Table 5
Different feedstocks for biodiesel production, oil yield, conversion efficiency, biodiesel yield and land requirement in Malaysia for B5 mandate [58].

Feedstock	Oil Yield (kg/ ha/ year)	Conversion efficiency (%)	Biodiesel Yield (kg/ha/ yr)	Amount of land required (thousand ha)	Percentage of arable land in Malaysia (%)
Soybean	375	95	356	1235	68.3
Rapeseed	1000	95	950	463	25.6
Jatropha	2000	98	1960	224	12.4
Palm oil	5000	94	4700	93	5.1
Microalgae*	75,000	80	60,000	7	0.4

*50% oil by weight in biomass.

this potential demand, a large cropping area is needed if Malaysia were to rely solely on palm oil resources for biodiesel feedstock. However, with the shift towards microalgae based biodiesel, smaller cropping area is needed for the same amount of yield, therefore eliminating the competition with land needed for food crops. Table 5 shows the land requirement comparison for various biodiesel feedstocks in Malaysia in order to meet its B5 mandate [68]. From the table, with a conservative conversion estimation of 80%, microalgae only require 7% of arable land for planting palm oil.

Since Malaysia is located in the tropical region containing rural area, microalgae can be produced in rural areas due to the availability of land with cheaper cost [111]. The laboratory and pilot scale microalgae cultivation for biofuel such as bioethanol, biodiesel is ongoing by researchers in Malaysia, Singapore, Brunei Darussalam and other south-east Asian countries [88,112,129]. To the authors' best knowledge, techno-economic analysis on microalgae-biodiesel with large scale production has not been conducted yet. However, a techno-economic analysis on microalgae-biodiesel on neighboring country, Singapore presented that microalgae can be cultivated using solar radiation and wastewater from industries the final cost of biodiesel from microalgae would be $0.42–97/L. This research also describes the potential for commercialization of algal biodiesel by means of simultaneous oil extraction and transesterification facilitated by ultrasonication method, which can be considered to be a cost-effective technique for making microalgae biodiesel more competitive with petrodiesel and approaching commercial realities [112]. Since there are lot of industrial sectors are looking for approaches to treat wastewater in Malaysia, utilizing this wastewater for microalgae harvesting and biodiesel production, Malaysia has fair chance to manage industrial funding as well as Government funding to treat sewage sludge and municipal waste [61]. Yet microalgae biodiesel has not been commercialized in the fuel market, therefore, no existing policy for microalgae-biodiesel has been implemented. However, there is an established Malaysian Government

Renewable Energy Policy called 'Bioenergy, Biofuels for Transports' of policy type 'Regulatory Instruments, Policy Support and Strategic Planning', under The Ministry of Plantation Industries and Commodities, Malaysia which is based on transportation fuel particularly biodiesel [113]. Since microalgae-biodiesel is type of biodiesel and transportation fuel, it can be commercialized with the existing transportation fuel policy in the country.

Based on the study of microalgae-biodiesel study of Malaysia, solely depending on producing biodiesel from microalgae will not be economically feasible, therefore, large-scale microalgae cultivation in Malaysia can be integrated with either with industrial wastewater treatment plant or shrimp, fish and tortoise farming in rural area and value-added products (protein and vitamin enriched) can be produced simultaneously beside biodiesel production to minimize the biomass production cost for biodiesel as well as turn the microalgae cultivation into multi-functional project. This study also reported that a mercantile microalgae-biodiesel scheme invested 68% of the total cost on capital expense (cultivation area, plant set up, instrumentation, process installation, and others) while similar type of microalgae-biodiesel plant set up only required 4% investment cost in a rural-desert area in China [114–116].

Apart from the potential local demand, the global demand can be seen as another prospect to further develop the biodiesel industry in Malaysia. A study conducted by the Center for Sustainability and the Natural Environment (SAGE) of the University of Wisconsin shows that the potential for biodiesel is enormous on a global scale [117,118]. Many researchers have conducted suitability of biodiesel for jet fuel and it is found as compatible [39,119–122]. Airbus, for example, believes that up to a third of aviation fuel could come from alternative source by 2030, which will undoubtedly increase the biodiesel demand [68]. Furthermore, the remaining reserve life of Malaysian crude oil is estimated to last for another 20 years [123]. Hence, to ensure consistent economic growth in Malaysia, the country should gradually increase its efforts in attaining alternative resources to replace the current dependence on petroleum fuel resource as well as on first generation biofuel and microalgae derived biodiesel is one such option.

The fundamental challenges which hinder the commercialization of biofuels in general are its lower energy density (plant biomass typically have lower energy density as compared to current fuel resources such as coal and crude oil) and the substantially high energy investment in order to grow, harvest and process plant biomass as compared to fossil fuels [78]. These two factors alone significantly influence the pricing of biodiesel and also the actual realization of biofuels being potentially carbon zero. Another challenge is to proceed with cost-effective microalgae based biorefinery which will be applied to obtain pure microalgae-biodiesel to blend with petro-diesel. Previous study on biorefinery in Malaysia presented that infrastructure in Malaysia supported biorefinery for municipal solid waste as well as agro-waste in Malaysia to emphasize on circular economy in the country [124]. Microalgal products such as nutrition supplement, feed, ingredients for cosmetic, medicine and others has been already commercialized in Malaysian as well as other south-Asian countries. Therefore, upon successful commercialization of microalgae-biofuel, microalgae biorefinery can be expected in the coming future in Malaysia.

As current energy sources largely depend on fossil fuels, coupled with the high energy investment required in the whole life cycle of microalgae based biodiesel, the pricing of microalgae based biodiesel can then be said to have large dependence upon fossil fuel prices, and will ultimately be higher than petrodiesel. This indicates that microalgae based biodiesel still has a long way to go before commercialization can actually be implemented. One way of doing so is investment in research and development. A recent technology of nano-additives with microalgae-biodiesel applications in IC engines can bring revolution in future for mercantile biodiesel production from microalgae in Malaysia. Nano-additives are usually efficient with either pure microalgae-biodiesel (B20) or mixture of petroleum diesel and microalgae-biodiesel in IC engines [125]. A current nano-additives study on microalgae biodiesel reported that using Nickel (Ni) dopped zinc-oxide (ZnO) nano-additives with the mixture of B20 and biodiesel from tropical microalgae, *Botryococcus braunii* effectively worked on IC engine by reducing greenhouse gases (e.g. CO_2, CO, hydrocarbons, oxides of nitrogen, soot and smoke) [126]. Other nano-additives application such as nano-La_2O_3, CeO_2, ZrO_2 blended with biodiesel from *Botryococcus braunii* can reduce the flue gas emission from the environment [125,127]. Industrialization of microalgae-biodiesel with nano-additives can initiate new window in biofuel market with more eco-friendly implications [128].

However, developing new industries requires not only technology but also trained experts such as scientists, engineers, technicians, as well as skilled business people. So far crop-based biofuel industries and policies have been established in many developing countries (including Malaysia), very few microalgae-based projects were encountered in existing literature [78]. A study conducted on microalgae found that the majority of microalgae based biofuel R&D took place in Europe and the US where they are responsible for 70% of the total publications related to algal biofuel despite having lesser potential zones for microalgae cultivation as compared to developing countries [78]. It is then evident that Malaysia, as one of the developing countries should strive further in terms of research and development for microalgae based biodiesel in order that its status as the leading biodiesel producer can be maintained even with the switch of current palm oil biodiesel feedstock to microalgae. Further research can be developed through government support through increased research grants, technology and knowledge transfer from collaborations with foreign universities/countries, an establishment of industry standard for biodiesel quality which can potentially increase the public's confidence in using biodiesel and providing biodiesel pumps at petrol stations to encourage biodiesel use amongst the public [68].

6. Conclusions

Malaysia has great potential for mass-production of microalgae for biodiesel productions. Due to favorable tropical region, adequate and inexpensive supply of nutrients, uninterruptible solar radiance throughout the year, high biomass productivity and lipid content, microalgae have been manifested higher potential candidate than other existing feedstocks. This study conducted a clear perspective of biodiesel production and application scenario from various feedstock in Malaysia while microalgae biodiesel could be new window for green fuel market in this region. Since biodiesel has been commercialized in the country already and proper policy implementation has been applied in Malaysia, commercialization of microalgae would require only adequate research to apply the optimum condition. Limitations and challenges of microalgae biodiesel production can be overcome by proper techno-economic analysis and life cycle assessment. Further microalgae studies in this area are recommended. In addition, some other significant factors can be considered for microalgae biodiesel production and application in Malaysia such as:

- ➢ Microalgae are equally effective to reduce GHGs emission growth besides nuclear and hydrogen energy, as well to satisfy the future energy demand for the country in the long term. Microalgae-based carbon fixation can be more attractive if its deployment is coupled with co-production of valuable downstream products and can potentially be coupled with carbon sequestration and wastewater treatment facilities.
- ➢ Biodiesel is one of the most potential downstream products apart from bioethanol and biogas. However, there is a lack of research in determining compatibility of biodiesel derived from microalgae for use in conventional diesel engines, especially after exposure to the power plant's flue gas. The future project shall study the compatibility of biodiesel produced from microalgae, to be used for power

generation and internal combustion engine application, through crude oil and biodiesel characterization tests.

- ➢ Productivity of microalgae biomass as well as well yield of microalgae biodiesel yield can be further enhanced by high-tech process mechanisms such as nano-additive application in different stages. In comparison with that, enhancement of biomass productivity of other biomass is much tougher compared to microalgae biomass.
- ➢ While palm oil is a popular cooking oil in Malaysia as well as many countries worldwide, elimination of palm oil use for biodiesel production by microalgae cultivation will contribute for food security as well as positive socio-economic impact.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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