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Review Paper

Advances in biofuel production from oil palm and palm oil processing wastes: A review

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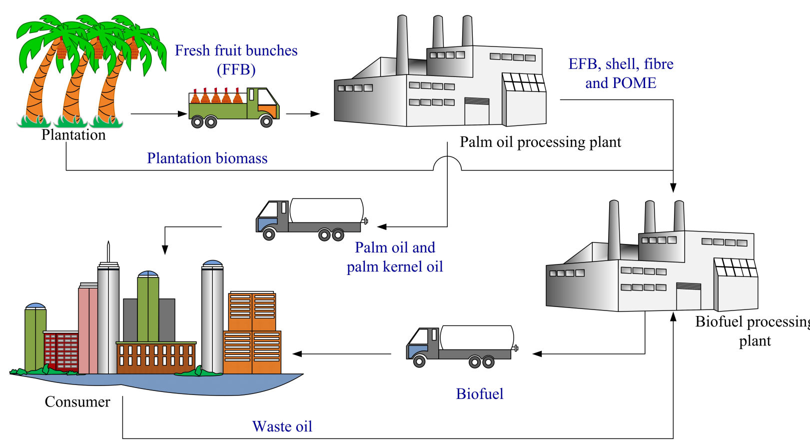
HIGHLIGHTS

- Technologies used for processing oil palm and palm oil wastes are reviewed.
- Major challenge in biofuel production from oil palm wastes is remote locations of palm plantations complicating transportation and distribution.
- Among phases in producing biofuel from oil palm wastes, oil palm plantation has the most severe environmental impacts.
- Development of cost-effective, environmentally friendly, and profitable biofuel production technologies from oil palm wastes is required.

GRAPHICAL ABSTRACT



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ABSTRACT

Over the last decades, the palm oil industry has been growing rapidly due to increasing demands for food, cosmetic, and hygienic products. Aside from producing palm oil, the industry generates a huge quantity of residues (dry and wet) which can be processed to produce biofuel. Driven by the necessity to find an alternative and renewable energy/fuel resources, numerous technologies have been developed and more are being developed to process oil-palm and palm-oil wastes into biofuel. To further develop these technologies, it is essential to understand the current stage of the industry and technology developments. The objective of this paper is to provide an overview of the palm oil industry, review technologies available to process oil palm and palm oil residues into biofuel, and to summarise the challenges that should be overcome for further development. The paper also discusses the research and development needs, technoeconomics, and life cycle analysis of biofuel production from oil-palm and palm-oil wastes.

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Contents

1. Introduction

The degradation of global environment and the prediction of the depletion of the fossil fuel resources have all encouraged the global community to search for alternative sustainable and environmentally-friendly energy resources. One of the most promising candidates is biomass energy. Despite its wide availability and relatively low cost in some locations, biomass energy has inherent drawbacks which hinder its wide utilization: low energy conversion, difficulty to transport and to store, and harmful effects of direct combustion of biomass. Often referred as traditional energy, biomass energy is commonly utilized in rural areas where other energy resources are not accessible due their availability or cost. Biomass is generally used for cooking and heating. To minimize the complexity of biomass transportation and storage as well as to avoid harmful effects of direct combustion of biomass, its conversion into biofuels is suggested (Baratieri et al., 2008). Biomass can be used to produce biofuels *via* different thermochemical and biochemical process such as biomethanation, fermentation, pyrolysis, and gasification (Verma et al., 2012; Akia et al., 2014).

Biomass sources can easily be found in our daily life including plant/crop roots, seeds, by-products/wastes, forest residues, municipal wastes, as well as cattle and human wastes (Verna et al., 2012). One tremendous source for biomass is palm oil industry. Palm oil itself is considered as a promising candidate to produce biofuel. Aside from producing palm oil, the industry also generates a huge quantity of residues (dry and wet) which can be processed to produce biofuels as well. In fact, the produced oil only contributes to 10 % of total biomass generated from plantations (Chew and Bhatia, 2008; Sulaiman and Taha, 2015). The other 90 % is disposed of as waste materials (e.g., empty fruit bunches, oil palm trunks, oil palm fronds, palm shells, palm pressed fibres, palm oil mill effluent, and old trees). In a specific location, the potential of biomass generated from oil palm industry is amounted up to seven times that of natural timber industry (Basiron and Chan, 2004). In addition to the biomass generated during palm oil production, the increasing rate of cooking oil consumption worldwide has also generated a huge amount of waste cooking oil which could trigger complex problems if not handled carefully. Currently, the waste cooking oil is discarded to the waste water stream, complicating waste water treatment, contaminating environmental water, and undermining its potential as biofuel feedstock. As such, disposing waste cooking oil to water drainage has been banned in the majority of the developed country (Kulkarni and Dalai, 2006).

Over last few years, there has been a growing interest to produce biofuel from vegetable oil especially palm oil. This is mainly driven by the desire to reduce greenhouse gas emission. The problems associated with the production of biofuel from palm oil are (i) biofuel from palm oil is not sufficient to compensate for global fuel consumption, (ii) it triggers food and fuel competition which may lead to high food price, and (iii) environmental degradation due to conversion of forests to oil palm plantations to excel the oil production (Sheil et al., 2009; Mukherjee and Sovacool, 2014). As such, an initiative has been put forth to produce the biofuel from oil palm and palm oil wastes. In line with that, numerous studies have been conducted and various processes have been proposed to produce biofuel from the oil palm and palm oil wastes (Amin et al., 2007; Geng, 2013; Awalludin et al., 2015). The methods presented vary according to the waste used as feedstock for biofuel production. The characteristics of the resultant biofuel also vary depending on the feedstock and method used. Hence it is important to summarize and discuss the main findings of these studies.

Therefore, the present paper is intended to comprehensively review the production of biofuel from oil palm and palm oil wastes and to investigate the various aspects that could potentially influence future advancements in the field. To achieve that, an overview on the palm oil industry, production processes, and current waste management scenarios is presented and discussed. Moreover, the technologies used for biofuel production from oil palm and palm oil wastes including their techno-economical aspects are also presented. Finally, the research and development needs for further advancements of the field are highlighted.

2. Palm oil industry

Grown in tropical regions, oil palm tree has been cultivated to produce palm oil which is widely consumed for food and other products. Here, the essential information on the oil palm and palm oil, production of palm oil, growth of oil palm industry, as well as the management and utilization of the wastes generated by the palm oil industry are presented.

2.1. Oil palm and palm oil

Palm oil is an edible vegetable oil extracted from the mesocarp of the fruit of oil-palm tree (*Elaeis guineensis*). The origin of this type of palm tree can be tracked to a region along the coastal strip of Africa between Liberia and Angola (Sheil et al., 2009). The tree can be raised in places with abundant rainfalls and heat such as tropical countries in Southeast Asia and South America. As such, large oil palm plantations can be easily found in these regions. Belonging to the subfamily Arecoideae, the morphology of oil palm is similar to the other palm species with a height up to 30 m (Edem, 2002). Generally, an oil palm tree starts to bear fruit after 3-4 years (Awalludin et al., 2015). The farmers need to wait for 5-6 months for the fruit to mature before they can harvest them. The fruit is plump-size, reddish in colour and is collated in a bunch weighting 10 to

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40 kg on average (Shuit et al., 2009). The fruit comprises exocarp, mesocarp, endocarp (shell), and endosperm (kernel). The mesocarp and endosperm contains 45-55% edible oil (Edem, 2002; Sumathi et al., 2008).

Oil palm is considered as the most efficient oilseed crop in the world due to its high productivity per hectare. Among the major oilseeds and oil plant (e.g., soybean, sunflower, rapeseed, groundnut, cotton), oil palm has higher oil production efficiency (oil produced/land area) of 4000 kg/ha (Yusoff and Hansen, 2007; Zulkifli et al., 2010; Salim et al., 2012). In addition, oil-palm has a long lifespan of over 200 years with relatively long economic life span of 25-30 years (Amin et al., 2007; Abdullah and Wahid, 2010; Rupani et al., 2010; Abdullah and Sulaiman, 2013), providing a reliable supply for oil production. Along with the high production efficiency, this has driven the rapid expansion of oil palm plantation around the globe.

2.2. Rapid growth of palm oil industry

Due to its affordable price, efficient production, and high oxidative stability, palm oil has been widely used in food, cosmetic, and hygienic products. From 2005, palm oil has replaced soybean oil as the most consumed edible oil globally. In 2012, consumption of palm oil reached 52.1 million tonnes worldwide (Sime Darby Plantation, 2014). Major palm oil consuming countries include China, India, Indonesia, and The European Union. In fact, driven by high market demands especially in the developing countries, the palm oil industry has grown rapidly over the last decades. During the 1950s to the early 60s, the average production of palm oil was roughly 1.26 million tonnes (Abdullah and Wahid, 2010). This increased to 5 million tonnes in 1980 and doubled to 11 million tonnes in 1990 (Abdullah and Sulaiman, 2013). Within 1995-2010, palm oil production expanded to 46.7 million tonnes (Mahat, 2012).

Although originated from Africa, oil-palm is widely cultivated in almost 43 countries in the tropical regions of Southeast Asia, Africa, and South America (Koh and Wilcove, 2008). Indonesia and Malaysia dominate the global production of palm-oil, contributing to around 85% of the palm oil production world-wide (Sime Darby Plantation, 2014; Siregar et al., 2014). Other major palm oil producing countries are Thailand, Columbia, Nigeria, Ecuador, and Papua New Guinea. Malaysia was the leading palm oil producer for a long period until 2006 when Indonesia overtook Malaysia to become the world largest palm oil producer. This is mainly attributed to the fast expansion of oil palm plantation areas in Indonesia and the stagnation of the oil palm plantation areas in Malaysia (Mahat, 2012).

This growing palm oil industry has changed the economy scenario especially in Malaysia and Indonesia as palm oil is one of the main export commodities for both countries. In fact, the palm oil industry has been a source of income and employment for the indigenous communities residing near the plantations and has led to substantial improvements in their life quality (Basiron, 2007; Mukherjee and Sovacool, 2014). The industry has also provided access to healthcare and education for the indigenous communities (Sheil et al., 2009). A study revealed that millions of people currently working in the oil palm industry, used to live in poverty (Wakker, 2006; Zen et al., 2006). In addition to that, the industry continues to generate huge revenues for the producing countries. Therefore, it is not surprising that the oil palm industry is expected to grow further in the coming years.

Despite its economic benefits and role as tool in poverty alleviation programs, the palm oil industry has received intense critics and negative reviews due to its land utilization expansion. The fast expansion of oil palm plantations has raised issues about the industry sustainability and its impact on the environment: destruction of old-growth rainforest and its biodiversity, air, soil and water pollutions as well as land disputes and social challenges. One way to address these issues is to increase the efficiency of the mills and plantations so that no or minimum further plantation expansion is required. Another way is to maximize the utilization of biomass produced in the plantations and mills to meet energy demands. This will reduce the cost of waste treatment and increase the profitability through the energy generated.

2.3. Palm oil production

Two distinct types of oil can be produced from oil palm fruit, i.e., crude palm oil (CPO) which is produced from the mesocarp and palm kernel oil which is produced from the kernel or endosperm (kernel) (Abdullah and Wahid, 2010; Mba et al., 2015). After harvested, the oil palm fruit should be transported quickly to the palm oil mill to be processed into palm oil. **Figure 1** shows the palm oil production process. Once the fresh fruit bunches (FFB) reach the processing plant, they will be sterilized by using steam. The FFB will then be stripped to separate the fruit from the stalk. The fruit will be directed to digesters and then pressers to extract the crude oil while the empty bunches will be collected to be used as fertilizer or dried before being fed into boilers. The oil extracted through the pressing process will be purified by using centrifugal and vacuum dryers before it is stored in storage tanks. CPO will be further processed in a refinery plant to produce cooking oil and other products. The other oil (i.e., palm kernel oil) is extracted from the nuts obtained from the pressing process. After fibre/nut separation, the nuts are sent to nut crackers and then to crushers to extract the kernel oil. Meanwhile, the shells and fibres are sent to boilers as fuel.

As can be observed in **Figure 1**, a palm oil mill plant is generally energy self-sufficient processing plant. The palm oil mill is commonly equipped with low pressure boilers. The wastes generated during the oil production process, mainly fibres and shells, are burnt as fuel in boilers to generate steam or hot gas for drying, sterilization, and power generation. Nevertheless, for the start-up process, a back-up diesel generator is generally installed to provide the initial power (Mahlia et al., 2001; Yusoff, 2006). It should be noted that not all wastes are burnt in boilers. Although the efficiency of boilers installed in mills is relatively low, some mills still have excess generated power which is distributed to the residential areas nearby. These areas are generally located in remote area where no electricity grid is available.

2.4. Oil palm and palm oil wastes: current disposal and utilization scenario

Palm oil industry generates a huge quantity of residues which can be processed to produce biofuel. As stated previously, in oil palm plantations, the extracted oil constitutes only 10% of the total biomass generated while the other 90% is considered as wastes. With rapid growing of palm oil industry, more residues will be generated, adding complexity to the current waste management procedures. On average, 50 to 70 tonnes of biomass residues are produced from each hectare of oil palm plantation (Shuit et al., 2009). The by-products or wastes generated from palm oil production includes oil palm trunk (OPT), oil palm frond (OPF), empty fruit bunch (EFB), mesocarp fruit fibre (MF), palm kernel shells (PKS), and palm oil mill effluent (POME). Except POME, these wastes have high fibre content.

In palm oil plantations, OPF is steadily available in the plantation throughout the year as harvesting is generally followed by pruning. In contrast, OPT is available only during the replanting season. As stated previously, oil palm trees have a relatively long lifespan and when they reach the end of their economic lifespan they should be replaced by new plants. The current practice is to leave the dead tress between the rows of palm trees to naturally decompose for soil conservation, erosion control, and in the long term nutrients recycling purpose. However, this practice poses the risk of attracting harmful insect to live and breed. In addition, leaving the trunk in the plantation will obstruct re-plantation activity. The other method is to utilize them as soil fertilizer by burning. This will minimize the risk of attracting insects; however, it results in air pollution. Open burning is commonly practiced in plantations in Indonesia causing hazardous air pollution not only in Indonesia but also in the neighbouring countries. Thick hazardous smoke generated from such open burning activities paralyses socio-economic activities in the nearby areas and therefore, many countries have raised their concern on this annual issue. In return, the Indonesian authorities stated that they would investigate and prosecute the plantation owners who practice open burning (The Jakarta Post, 2015). Nevertheless, it is believed that legal prosecutions alone would be insufficient and that to eliminate this problem, a more efficient and environmentally-friendly utilization of the generated OPT and OPF during the replanting session is urgently needed.

Other than its application as fertilizer, OPF can also be chopped into small pieces, mixed with other ingredients, and utilized as livestock feed (Abu Hassan et al., 1996). Several studies were conducted to examine this possibility and proposed an integrated crop-livestock system where the livestock farm should be located inside the oil palm plantation (Abu Hassan et al., 1996).

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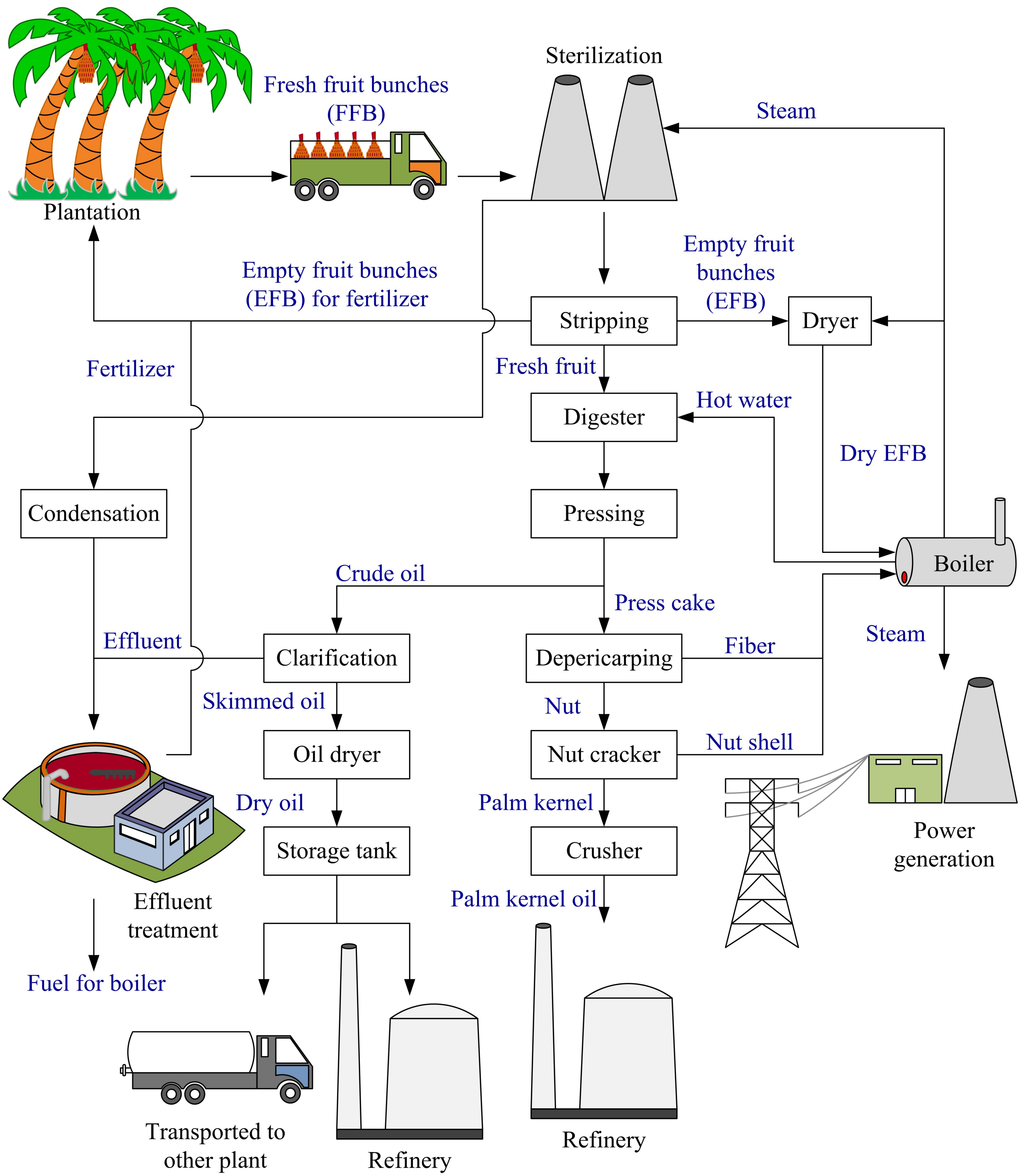

Fig.1. Palm oil production process (adapted from Abdullah and Sulaiman, 2013).

EFB, MF, and PKS are generally used as fuel in mill boilers. The ash generated in boilers is transported back to plantations as fertilizer (Shuit et al., 2009). It is worth mentioning that EFB cannot be burned directly due to its high moisture content resulting in low heating value and air pollutions (Abdullah and Sulaiman, 2013), and therefore, it should be dried using hot air until its moisture content is significantly decreased. Hence, MF and PKS are more desirable as boiler fuel while EFB is usually dumped in plantations (Chew and Bhatia, 2008; Awalludin et al., 2015).

Aside from being used as soil fertilizer and boiler fuel, there is a growing interest to use EFB to produce bioplastics (Abdullah et al., 2011; Siyamak, 2012; Tan et al., 2014). The characteristics of bioplastic are similar to those of fossil fuel-derived plastics, making them suitable to produce biodegradable foil, moulds, tins, cups, bottles, and other packaging materials (Shuit et al., 2009). Palm fibres, i.e., MF produced during the palm oil processing can be used as fillers in the production of thermo-plastics and thermoset composites which have wide applications in furniture and automobile components (Shuit et al., 2009). The oil palm biomass can also be utilized to produce absorbents for toxic gas and heavy metal. For instance, the waste generated through burning PKS and MF in boilers can be converted into absorbents for pollutant removal. This waste has been found to contain high concentrations of silica, calcium, potassium, and alumina which are essential in absorbents production (Zainudin et al., 2005; Mohamed et al., 2006).

Currently, relatively low efficient boilers are installed in mills to produce steam for sterilization, drying, and power generation. Installation of more efficient co-generation plants is strongly advisable to generate more energy and reduce emissions. However, the challenge is that under the current conditions, mill cannot sell their excess electricity to the grid and hence, the installation of new plants is not economically justified.

The only liquid waste produced from the palm mill is POME. It mainly consists of water with small amounts of solid and oil. The processes that generate huge amounts of POME in palm oil processing plants include sterilization, crude oil clarification, and cracked mixture separation (Rupani et al., 2010). In fact, this huge amount of POME is the result of the tremendous amount of water used to clean up the palm fruit and to extract the oil from the mesocarps. To extract 1 ton of crude palm oil, approximately 5-7.5 tons of water is used, out of which more than half (i.e., >2.5-3.75 tons) ends up as POME (Ma, 1999; Ahmad et al., 2003). Even though it is considered as non-toxic material, POME cannot be discharged to the environment directly without treatment as it is acidic and contains residual oil which cannot be easily separated using the gravitational method (Madaki and Seng, 2013). If the raw or untreated POME is discharged to rivers, it will extensively consume and deplete the dissolved oxygen content essential for the aquatic life.

POME contains high concentrations of organic compounds such as protein, carbohydrate, nitrogenous compounds, lipids, and minerals, making it suitable as plant fertilizer provided that it is properly treated (Habib et al., 1997; Muhrizal et al., 2006). The current disposal scenario for POME is to store it in anaerobic and aerobic digestion ponds before being discharged into rivers. Anaerobic ponds if covered are more desirable as they use less energy, produce minimum sludge, does not results in unpleasant odour, and offer efficient breakdown of organic substances to produce methane-rich biogas which can be used as fuel (Rincon et al., 2006; Rupani et al., 2010). Before it can be deposited into digestion ponds, however, POME has to be passed through several physical pre-treatment processes including screening, sedimentation, and oil removal. Due to its generally low cost, the pond system has been widely adopted by palm oil mills. This method however, requires a large area of land and relatively long hydraulic retention time (HRT) which often creates a problem of discharging incompletely-treated POME into water bodies. In addition to that, in most open pond systems, due to the difficulty in collecting the generated biogas, the gas is directly released to the environment, wasting its potential as an alternative environmentally-friendly fuel and contributing to the greenhouse gas emissions. To overcome this, there are initiatives proposed to install closed anaerobic pond systems where the high quality methane-rich biogas can be collected (Abdullah and Sulaiman, 2013).

In addition to the biomass waste produced during the palm oil production, the palm oil consumption also generates a huge deal of waste in the form of used cooking oil. In recent years, the demand for palm oil has grown significantly especially by the developing countries due to their rapid population and per capita income growth. In fact, palm oil is mainly used in food industries and households for cooking (frying). During frying, the fatty acids contained in palm oil undergo multiple reactions such as oxidation, polymerization, and hydrolysis, and therefore, should be disposed of to avoid human health and nutrition problems (Naghshineh and Mirhosseini, 2010; Stier, 2013). The disposal of used cooking oil is tricky as its direct discharge into the water drainage system pose serious environmental threats. A more economical and environmentally-friendly disposal method is by its collection and conversion into biofuel (i.e., biodiesel) to be used as an alternative to fossil-derived diesel fuel. It should also be highlighted that the biodiesel produced from waste cooking oil is considered to be carbon neutral as the carbon emissions released from biodiesel combustion are compensated by those absorbed by palm oil trees during the photosynthesis process (Sheil et al., 2009).

2.5. Challenges in utilization of oil palm and palm oil wastes

In the current waste management scenario, the biomass residues generated by oil palm plantations and mills are underutilized. Therefore, there is a need to explore and evaluate various strategies to maximize the utilization of these biomass wastes. However, there are several roadblocks that hinder its further advancement and need to be overcome. Some of these are summarized as follows:

- *Location of plantation in remote area*

As mentioned earlier, plantations are commonly located in remote areas where no electricity grid is available and hence, the excess electricity generated by the power plants in the palm oil mills cannot be sold. This makes the installation of power plants with higher capacities and efficiencies not economically feasible. Consequently, the utilization of biomass generated in plantations and mills for power generation is also hindered.

Moreover, aalthough OPF could be potentially used as animal feed but it needs to be transported from plantations to livestock farms. This will lead to additional carbon emissions through the transportation. Therefore, as mentioned earlier, integrate livestock farming inside oil palm plantations should be considered.

- *Large open digestion ponds*

Another challenge currently faced is the large amount of biogas released into the atmosphere from the POME treatment ponds. This is ascribed to the fact that the main purpose of the currently in-use digestion ponds is not to produce biogas but to decompose the organic compounds of the POME so that it can be safely discharged into rivers. This practice also undermines the potential of POME to produce an environmentally-friendly fuel, i.e., biomethane. The obstacle to collect the biogas from the current open ponding systems is the large area of ponds making it difficult to collect the biogas. In addition, the conditions inside the ponds cannot be thoroughly controlled; hence the production of biogas fluctuates. Another problem is the utilization of the produced biogas because the boilers installed in palm oil mills are commonly designed to be fuelled with mesocarp fibres and palm kernel shell. To change the boilers will impose additional cost on the mills. A possible utilization strategy is to sell the produced gas to other parties. However, the compression and transportation of the gas will be challenging.

- *Collection process and quality of used cooking oils*

In case of the waste cooking oil utilization, although producing biodiesel is the most economical and environmentally-friendly disposal strategy, the collection of the oil from various locations (restaurant, food factories, and households) is challenging. Currently, in most countries, there are no dedicated pipelines to collect the waste cooking oil and it is mostly collected manually from every households. The other challenge faced in the utilization of waste cooking oil as biodiesel feedstock is the varying characteristics of the oil since it is exposed to various cooking conditions leading to different oil compositions and structures. Hence, additional pre-treatment may be required before it can be converted into biodiesel.

3. Production of biofuel from oil palm and palm oil wastes

The different types of palm oil biomass along with the waste palm oil itself are effective resources to produce biofuel. Palm oil makes up 33% of the global vegetable oil production catering for the domestic and export needs of many countries such as Malaysia, Indonesia, and Thailand (Pool, 2014). The extensive use of palm oil in cooking, lubrication, cosmetics, etc. generates a huge quantity of waste palm oil as well. Furthermore, the biomass generated during the palm oil production is also a potential source for sustainable energy production. It has been reported that for every kilogram of palm oil produced, four kilograms of wastes in the form of fibrous strands of empty fruit bunch are also generated (Law et al., 2007). Several attempts have been made over the last couple of decades to convert these wastes into useful products such as hydrogen, transportation fuels, liquid and gaseous hydrocarbons, briquettes, etc. (Marquevich et al., 1999; Demirbaş, 2005; Huber and Corma, 2007; Nasrin et al., 2008; Pütün et al., 2008; Balat et al., 2009; Misson et al., 2009; Sulaiman and Abdullah, 2011). Chew and Bhatia (2008) reviewed the literature extensively with regards to different catalytic technologies involved in utilizing the palm oil and palm oil biomass as well.

This section attempts to review different energy conversion technologies for the conversion of liquid palm oil wastes as well as solid waste fibers.

3.1. Production of biofuel from palm oil

Figure 2 shows an outline of different processing technologies used for biofuel production from palm oil. The biofuel production from palm oil can be divided into two main categories, i.e., catalytic cracking and transesterification. Historically, transesterification has been used for centuries to produce glycerin from vegetable oil which is used in the manufacturing of soap. Initial attempts to use transesterification for biodiesel production date back to the early twentieth century (Mamilla et al., 2012). However, due to the increasing environmental concerns and exhaustion of fossil fuels, the focus has been shifted significantly to vegetable oil derived biofuels.

Alternatively, catalytic cracking is also used to convert high molecular weight vegetable oils into lighter and more useful hydrocarbons. Amongst the two technologies, the catalytic cracking process is more developed since it has been extensively utilized to get the desired petroleum products such as diesel, gasoline, olefins, etc. from crude oil. The following discussion presents a technological evaluation of the transesterification and the catalytic cracking.

3.1.1. Transesterification

Palm oil is well-known vegetable oil feedstock to produce biodiesel through the transesterification process. Transesterification is a process by which triglycerides (vegetable oil) react with an alcohol (methanol or ethanol) to form fatty acid methyl/ethyl esters and glycerol (Korus, 1993). The esters derived from vegetable oils are very similar to petro-diesel in terms of cetane number, viscosity, and energy content (Darnoko and Cheryan, 2000), thus aptly named as 'biodiesel'. Amongst different types of vegetable oils, palm oil holds significant potentials in meeting energy demands owing to its high yield (Pool, 2014). Due to this, many countries located in the Association of South East Asian Nations (ASEAN) region like Malaysia, Indonesia, Thailand, etc. have focused on utilizing palm oil to produce biodiesel.

There are different operational parameters which could impact the overall efficiency and yield of the transesterification process. These include, 1) temperature of the mixture, 2) moisture quantity in the mixture, 3) mass transport (intensity of mixing), 4) molar ratio of alcohol to vegetable oil, and 5) type of catalyst (Korus, 1993; Mamilla et al., 2012).

A detailed study of chemical kinetics is important in optimizing the yield of the reaction and reaction time. Unlike diesel produced from crude oil, very limited kinetic data are available on biodiesel produced from vegetable oils. Darnoko and Cheryan (2000) were amongst the pioneers who developed the chemical kinetics for the 3-step transesterification of palm oil. The study was followed by a series of experimental investigations aimed at determining the impact of the catalyst type, temperature, and alcohol to oil ratio on the overall yield of the process.

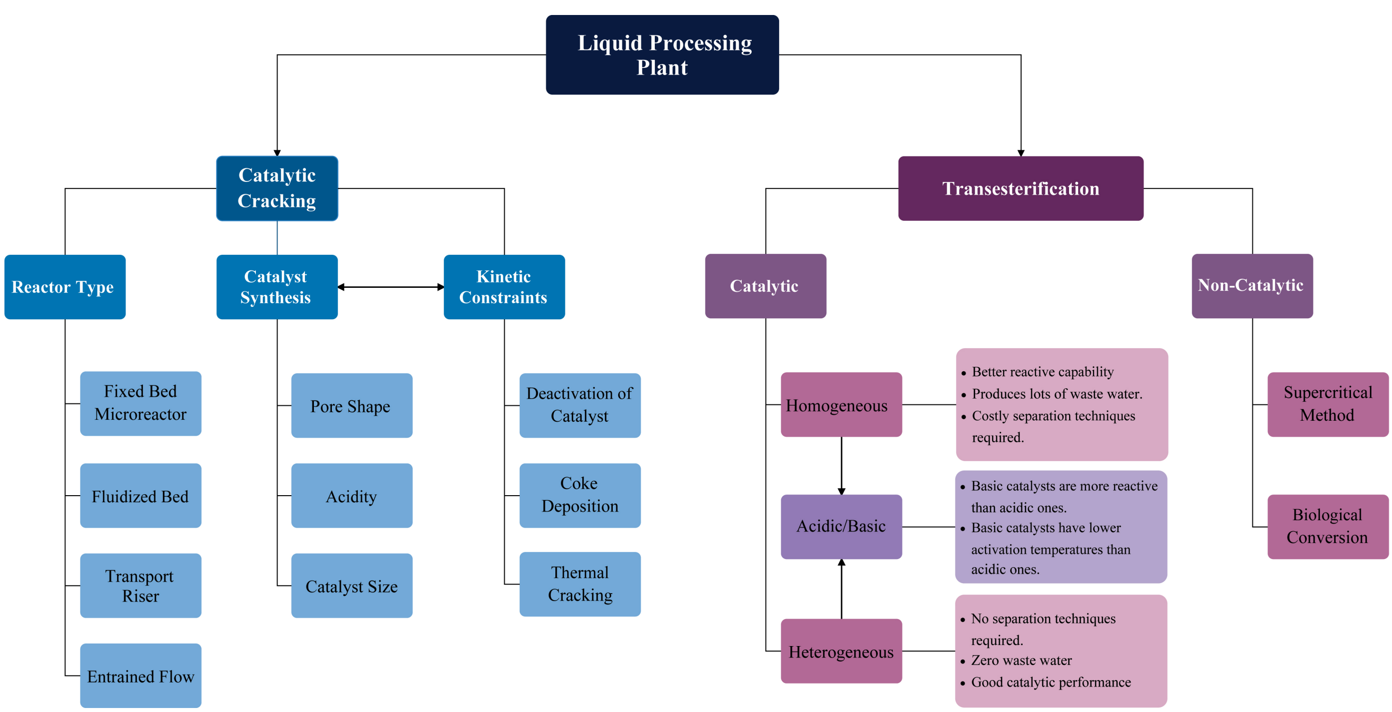

Fig.2. Overview of different processing technologies used for biofuel production from palm oil.

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- *Optimization studies*

Table 1 presents a comparative overview of different experimental studies dedicated to biodiesel production from palm oil. Most of these studies used methanol as acid in the transesterfication reaction since the physical and chemical properties of methyl esters are very close to those of petro-diesel. All of the above-mentioned studies have attempted to optimize the impacts of different factors such as catalyst loading, alcohol to oil ratio, reactor temperature, reaction time, and type of catalyst used on biodiesel production. Several studies have also considered the impact of different process variables involving preparation of the catalyst but it is beyond the scope of this review and hence not discussed further (Kansedo et al., 2009; Chen et al., 2015)

Since the yield of palm oil transesterification process is dependent upon a wide variety of parameters pertaining to reactor system configuration, catalytic synthesis. and operating conditions, optimization of all these parameters is not straightforward. Hence, researchers have used different statistical techniques such as Taguchi method (Chongkhong et al., 2007) and Response Surface Methodology (RSM) (Mootabadi and Abdullah, 2015) to obtain the optimum values of the kinetic parameters leading to the maximum yield of fatty acid methanol ester (FAME) was. In a recent study, Mootabadi and Abdullah (2015) used the RSM to optimize an ultrasound-assisted transesterification process.

- *Effect of catalyst type on transesterification*

From the studies tabulated in **Table 1**, it can be inferred that process yield depends on catalyst type, reaction conditions, and catalyst treatment parameters. Different classes of catalysts have been utilized to determine the optimum reaction conditions for biodiesel production from palm oil. Traditionally, homogenous base catalysts are used due to their high catalytic activity and wide availability. However, their use limits the overall yield and reusability of the catalyst since they require additional processing for separation. The downstream process used to wash away the base catalyst residues (typically NaOH or KOH) also results in lots of toxic waste (Ma and Hanna, 1999; Gao et al., 2008; Noiroj et al., 2009). An additional disadvantage is that the homogeneous base catalysts are not suitable for raw materials containing high water and free fatty acids contents (Gao et al., 2008). These factors resulted in a lookout for a new and improved catalytic technology which can remove the additional purification and separation process without compromising the overall yield. It is worth mentioning that although there are some studies in which using acid based catalyst was investigated (Al-Widyan and Al-Shyoukh, 2002; Chongkhong et al., 2007), but due to the low catalytic activity of these catalysts as well as their requirement for high reactor temperatures, their use has been discouraged. So, in most of the biodiesel production studies from palm and other vegetable oils, basic catalysts are still used because of their enhanced catalytic reactivity.

Given the above-mentioned disadvantages of the homogeneous catalyst, the use of heterogeneous (mostly solid) catalysts for the transesterification process of palm oil was adopted (Bo et al., 2007; Kawashima et al., 2008; Gao et al., 2008; Kansedo et al., 2009; Chen et al., 2015). Although the use of solid catalysts simplified the process, however, they have several technological shortcomings. To address these challenges over the last decade, the research in the area of catalytic development has been steered towards investigating the impacts of different combinations of metallic oxides and zeolites along with analysing catalyst synthesis techniques and conditions on the process yield and durability of the catalyst. Kawashima et al. (2008), for instance, analysed the catalytic performance of a wide variety of metallic oxides including Calcium, Magnesium, Barium, and Lanthanum. They concluded that oxides of Calcium enhanced catalytic performance compared with the other metallic oxides investigated. They attributed their findings to the surface structure of the catalyst, i.e., favourable porosity and basicity compared with the other metallic oxides. Other commonly used metal oxides reported in the literature are NaO and TiO_2 (Kawashima et al., 2008).

- *Use of renewable resources to synthesize catalysts*

Due to the increasing attention towards the use of renewable resources to meet our energy demands, the research in this area has also been recently shifted towards developing catalysts from renewable resources and enhancing the reusability of the catalysts while maintaining the yield.

Table 1.
Optimum parameters for different transesterification studies.

Catalyst Used	Alcohol Used	Optimum Catalyst Loading (%; wt./wt. oil)	Optimum Alcohol to Oil Molar Ratio	Reactor Temperature (°C)	Optimum Reaction Time (h)	Yield (%)	Reference
Rice husk ash	Methanol	7	9 to 1	65	4	91.5	Chen et al. (2015)
CaO	Methanol	5	6 to 1	65	3	93.2	Chen et al. (2015)
KF/Al_2O_3	Methanol	4	12 to 1	65	3	90	Bo et al. (2007)
13 different metal oxides of Ca, Ba, Mg, La	Methanol	-	6 to 1	60	10	79-92	Kawashima et al. (2008)
KF/Hydrotalcite	Methanol	3	12 to 1	65	3	90	Gao et al. (2008)
CaO/ZnO	Methanol	10	30 to 1	60	1	94	Ngamcharussrivichai et al. (2008)
KOH/Al_2O_3	Methanol	25	15 to 1	60	2	91.07	Noiroj et al. (2009)
KOH/NaY	Methanol	10	15 to 1	60	3	91.07	Noiroj et al. (2009)
H_2SO_4 and HCl	Ethanol	-	100 % excess ethanol	90	3	-	Al-Widyan and Al-Shyoukh (2002)
NaOH	Methanol	0.38	5 to 1	60	3 to 4	92	Mamilla et al. (2012)
$SO4^{2-}/ZrO_2$	Methanol	1	6 to 1	200	1	90.3	Jitputti et al. (2006)
Montmorillonite KSF	Methanol	3	8 to 1	190	3	79.6	Kansedo et al. (2009)
H_2SO_4	Methanol	1.834	4.3 to 1	70	1	93.9	Chongkhong et al. (2007)

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Table 2.
Reactor type and yield comparison for catalytic cracking of palm oil.

Reactor Type	Catalyst Used	Operating Temperature (°C)	Conversion of Palm Oil (%)	Yield (product) (%)	Reference
Batch reactor	Na_2CO_3	450	-	65.86 (Organic Liquid Products)	Da Mota et al. (2014)
Fixed bed micro-reactor	Various zeolite catalysts	350-450	99	28 (Gasoline)	Twaiq et al. (1999)
Transport riser reactor	Zeolite REY	450	74.9	59.1 (Gasoline)	Tamunaidu and Bhatia (2007)
Fixed bed micro-reactor	HZSM-5 (microporous) MCM-41 (mesoporous)	450	99	48% (Gasoline)	Sang (2003)
-	V_2O_5, MoO_3, ZnO, CO_3O_4, $ZnCl_2$	320	77.6	33.62% (Gasoline)	Yigezu and Muthukumar (2014)
Fixed bed micro-reactor	Nanocrystalline zeolite beta and zeolite Y	450	84	53% (OLP), 35% (Gasoline)	Taufiqurrahmi et al. (2010)

Chen et al. (2003) demonstrated the use of renewable resources such as rice husk ash in synthesizing the CaO catalyst for biodiesel production from palm oil. Moreover, Shan et al. (2015) investigated the impact of sodium poly styrenesulfonate induced mineralization and calcination of CaO on the enhancement of the catalytic activity and reusability of the catalyst. In their study, not only the trasesterification yield of palm oil was improved, the reusability was also enhanced as compared with the traditional CaO catalyst. In another study by Wong et al. (2015), a biodiesel yield of 95% was achieved by using a combination of Calcium and Cerium oxides. Moreover, the synthesized catalyst could be reused 6 times without significant losses in the yield.

- *Non-catalytic approaches to transesterification*

Besides the catalytic approach, other methods have also been studied to carry out transesterification reaction of palm oil effectively. One of such novel approaches is using supercritical methanol for the alcoholysis of the palm oil (Joelianingsih et al., 2008; Song et al., 2008). This approach can significantly reduce the reaction time and also eliminate any complex pre- and post-treatment steps for the catalyst and the reaction mixture, respectively. Supercritical transesterification uses methanol in a supercritical state (high temperature and high pressure) to react with the triglycerides. This results in very fast reaction kinetics and a high final yield of biodiesel. Furthermore, as mentioned earlier, it simplifies the overall process by eliminating pretreatment, soap removal, and catalyst removal processes altogether (van Kasteren and Nisworo, 2007). One of the main disadvantages of this process is the harsh reaction conditions required (i.e., high temperature and pressure) which complicate the reactor design.

3.1.2. *Catalytic cracking*

One of the main disadvantages of using biodiesel as fuel is that it generally cannot be used in its pure form in engines, gas turbines, etc. and it needs to be blended with petro-diesel. Furthermore, the technology is still not economically competitive with the petro-diesel (Pool, 2014). Unlike transesterification, catalytic cracking is a mature technology since it has been being used to convert crude oil into useful olefins and paraffins for almost a century now. Another obvious advantage is that cracking of oil yields gasoline, diesel, and kerosene directly. Catalytic cracking of palm oil to obtain bio-gasoline has been a subject of many studies in the literature (Chew and Bhatia, 2008). The process involves breaking the heavier chains of fatty acids contained in palm oil into lighter and more useful products such as olefins, paraffins, ketones, and aldehydes. According to the literature, the important factors affecting the catalytic cracking process are, 1) type of reactor, 2) catalyst synthesis, and 3) reaction conditions (temperature, residence time, etc.) (Twaiq et al., 1999; Sang, 2003; Taufiqurrahmi et al., 2011). It should be mentioned that all the three factors are dependent upon each other making the optimization of the process complex.

- *Choice of reactor for catalytic cracking*

There are several key process variables and operational constraints which influence the choice and design of the reactor. Factors such as process chemistry, kinetics of the cracking process, deactivation of catalyst due to coke deposition, thermal cracking, cracking temperature, and adjustment of residence *vs.* contact time of the catalyst, etc. must be considered carefully when constructing the reactor (Avidan and Shinnar, 1990; Ong and Bhatia, 2010).

At laboratory scale, there are different reaction setups that have been analysed in the literature for catalytic cracking of palm oil. The most commonly used reaction systems are fixed bed, fluidized bed, transport-riser, and entrained flow reactors. Almost all of the afore-mentioned reactor types are designed for heterogeneous operation (i.e., solid-gas interface) (Miller and Jackson, 2004), aiming at enhancing the contact area between the solid catalyst and the liquid fuel. Most of the experimental setups carrying out fluid catalytic cracking (FCC) employ a fluidized bed system due to various reasons. Firstly, it allows for continuous operation of the reactor and ensures uniformity of the product. Secondly, if employed on a large scale, it lowers the production cost as compared with the other technologies (Ong and Bhatia, 2010).

The problems of coke deposition, residence, and contact time optimization are the major issues driving the design of chemical reactors. Coke deposition in particular is very detrimental since it significantly limits the catalytic activity and therefore, excessive regeneration of the catalyst will be required making the continuous production difficult (Bhatia et al., 2007; Chew and Bhatia, 2008). Hence, the kinetics of coke formation should be known and reactors should be designed in such a way so as to limit its production. Research in this area indicates that in order to achieve a trade-off between the gasoline yield and coke production, the reactor should be designed to have short contact times between the catalyst and the atomized fuel while operating at high temperatures (Tamunaidu and Bhatia, 2007; Kansedoet al., 2009; Taufiqurrahmi et al., 2010). For such an application, a transport riser reactor serves the purpose well since it allows for continuous operation while ensuring short contact times. This leads to lower coke deposition and in turn highest gasoline production amongst all other reactor types as demonstrated in **Table 2**.

- *Effect of catalyst*

The efficiency and economic feasibility of the FCC process is a strong function of type and synthesis of catalyst. Key properties that influence the catalytic activity in the cracking reaction are acidity, size, pore shape, and selectivity. **Table 2** compares the conversion and yield (mostly bio-gasoline) from the cracking of palm oil. A review of these studies indicates that zeolites are the most widely used catalysts for fluid cracking. In fact, a wide variety of studies in the literature assessed the performance of different zeolite catalysts such as HZSM-5, zeolite-β and

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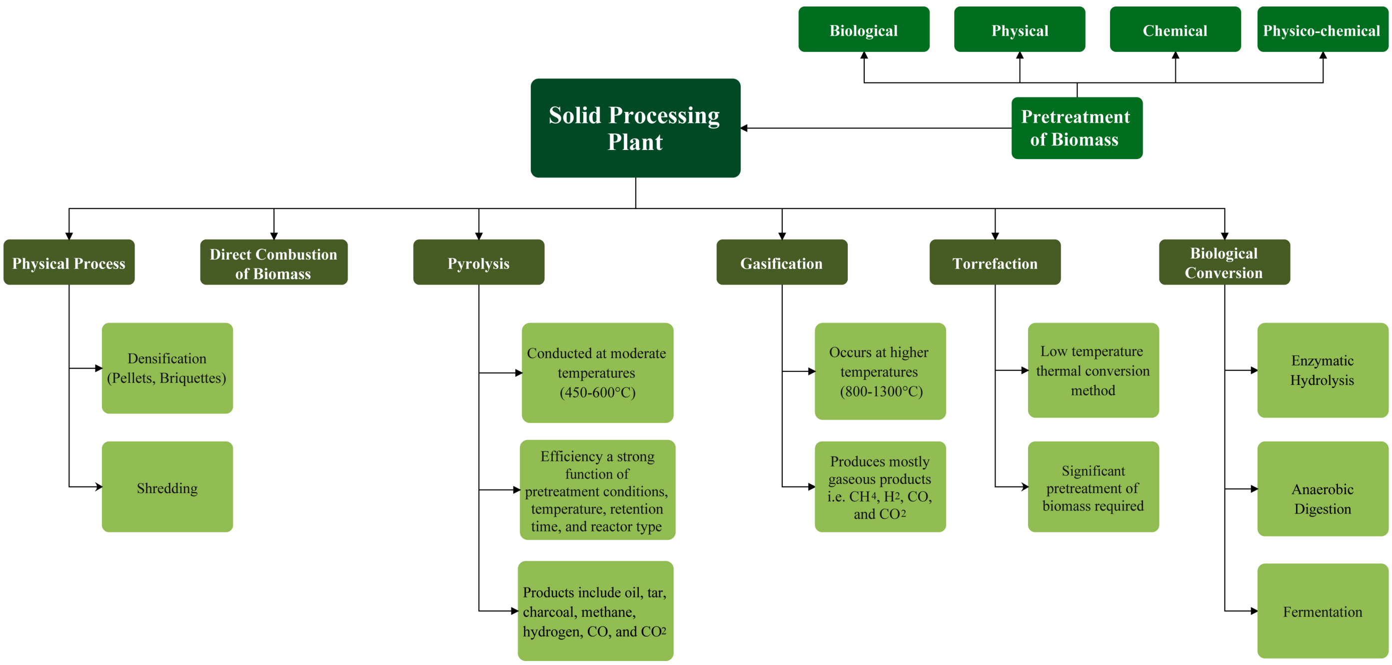

Fig.3. Overview of solid processing technologies for palm oil biomass.

USY, on overall palm oil conversion and gasoline yield (Adjaye et al., 1996; Leng et al., 1999; Twaiq et al., 1999). Amongst these catalysts, HZSM-5 reportedly led to the best results in terms of palm oil conversion, yield of bio-gasoline, and lower coke formation. The other zeolite catalyst enhanced the coke formation kinetics due to their bigger channel intersections. HZSM-5 on the other hand due to its higher acidity and shape selectivity yielded better results.

Apart from zeolites, another important class of catalysts used in the catalytic cracking of palm oil are microporous and mesoporous type such as CZM and MCM-41, etc. Sang (2003) analysed the impact of microporous, mesoporous, and composite (micromesoporous) catalysts on the overall conversion of palm oil and bio-gasoline yield. It was found that micromesoporous catalyst yielded best results in terms of the desired gasoline and palm oil conversion since it enhanced both acidity and pore size of the catalyst (Sang, 2003)

- *The state of the art and future avenues*

According to different comparative studies, palm oil has the highest oil yield and is the most economic source amongst all other vegetable oils. As elaborated, there are two major technologies by which palm oil is converted into biofuels namely transesterification and catalytic cracking.

The state of the art along with future directions regarding transesterification of palm oil can be summarized as follows:

- Catalytic transesterification is more technologically developed and hence widely used.
- Use of heterogeneous catalysts is encouraged for catalytic transesterification since they make the catalyst separation from the biodiesel easier preventing a lot of water from being wasted in the process.
- The current research in this area is directed towards enhancing the reactivity of the heterogeneous catalysts using novel pretreatment techniques. The techniques include mineralization with different metal.
- oxides and zeolites, temperature treatment, and combining oxides of different metals in optimum proportion.
- Use of renewable resources to synthesize catalysts and to improve their reusability is also a research area of interest.
- In the transesterification reaction, the use of supercritical methanol makes the overall process simple and improves the overall yield. However, the high pressure and high temperature conditions required for supercritical methanol transesterification require sophisticated reactor design and high energy input.

As for catalytic cracking process, the state of the art and the potential improvements in the future can be summarized as follows:

- Choice of reactor and catalyst synthesis are two major points of interests in catalytic cracking process.
- Transport-riser reactor is recommended for catalytic cracking process since it allows for continuous operation and reduces the coke deposition in the reactor.
- Future research in this area should aim for enhancing the catalyst regeneration through improved reactor design.
- Development of microporous, mesoporous, and micromesoporous catalysts to improve acidity and to optimize pore size is an active area of research.

3.2. Biofuels production using oil palm biomass

As mentioned earlier, lots of biomass is produced as wastes from the production of palm oil. Originating from different parts of the palm tree such as empty fruit bunches, fronds, trunks, palm pressed fibres and palm shells, the lignocellulosic materials of the palm oil biomass have a lot of energy content which if utilized properly can meet a part of the present energy needs. In order to achieve this objective, several challenges associated with different biomass sources such as lower energy content and higher energy consumption for collection, difficulty in transport and uneven composition, etc., have to be addressed.

Biofuel production from oil palm biomass involves a wide range of methods. Most of these technologies involve turning the biomass into liquid-gaseous mixture form and then upgrading (decreasing water and oxygenated compounds contents) the liquid mixture to render it suitable for burning purposes. **Figure 3** gives an overview of different solid processing methods that have been employed for utilizing the energy of palm oil biomass. Methods such as gasification, torrefaction, pyrolysis, and direct combustion come under the category of thermochemical energy conversion methods. Fermentation, enzymatic hydrolysis, and anaerobic digestion are classified under biological conversion methods whereas densification and shedding come under physical processes. The thermochemical processes require more energy input than the other categories. However, in terms of the process yield and large scale production, thermochemical technologies are more suitable. Most of the current efforts are focused on thermochemical energy conversion domain since the resultant liquid products possess higher energy densities (Bridgwater and Bridge, 1991). Accordingly, these methods are discussed here in further detail.

3.2.1. Pyrolysis of palm oil biomass

The process of pyrolysis involves converting the organic matters into bio oils by burning it with very little or no oxygen. The resulting products comprise of a wide variety of solid, gaseous, and liquid materials such as char, coke, bio-oil, CO_2, CO, CH_4, and H_2, etc. Amongst these products, bio-oil, CH_4, and H_2 have high heating values and thus, can be used as replacement of fossil fuels (Bridgwater and Bridge, 1991). Literature shows that the maximum yield of bio-oil can be obtained by operating the reactors at high heating rates and short gas residence times (Chen et al., 2003; Chew and Bhatia, 2008). Furthermore, the maximum yield is also dependent upon the cellulosic content of the palm oil biomass and the type of reactor (Demirbaş, 2001). The pyrolysis process itself does not require any catalysts. However, catalysts play a very important role in deoxygenation and upgrading of the liquid fuel obtained by the pyrolysis. This ultimately impacts the fuel quality of the resulting biofuels such as bio-oil, H_2, and CH_4, etc.

Table 3 presents a comparison of the reactor technology, yield of bio-oil, and pretreatment conditions employed by different palm oil biomass studies. Most of the studies shown in the table only reported fast pyrolysis reaction of biomass without catalytic upgrading of the resultant bio-oil. The highest yield was reported for the biomass of the EFB conducted by Asadieraghi and Daud (2015). This could be attributed to the high volatile content of the EFB biomass.

hydrogen. Furthermore, using Fischer tropsch synthesis, the synthesis gas obtained from direct gasification can further be processed to yield transportation fuels like bio-gasoline, diesel, naphta, etc. (Chew and Bhatia, 2008). However, the further processing of the synthesis gas requires effective catalytic systems and reactor designs. Accordingly, a wide number of studies have examined the conversion efficiency of various combination of catalysts, such as zeolites, metallic oxides, microporous and mesoporous surfaces, etc., as well as different reactor designs (Kelly-Yong et al., 2007; Lahijani and Zainal, 2011; Mohammed et al., 2011). Lahijani and Zainal (2011) in their study achieved a carbon conversion efficiency of 93% and 85% for EFB and sawdust biomass, respectively, in a bubbling fluidized bed reactor setup. For EFB, particle agglomeration was a major problem at higher reactor temperatures (>1000 °C). However, for saw dust biomass, agglomeration never occurred even at high temperatures. Chew and Bhatia (2008) investigated different types of catalysts used in the process of higher alcohol synthesis (HAS) from biomass. The HAS process was operated at 250°C - 425°C and 30 - 330 bar, depending upon the catalyst type. Different metal oxides and alkaline catalysts were tested and their operating conditions along with final product types were reported. Thy found out that metal catalyst were prone to deactivation in case of sulphur impurities in the water gas. Amongst the different metallic catalysts tried, such as Rhodium, MoS_2, Cr_2O_3, ZnO etc., no clear ‘leader’ in terms of catalytic performance was found. Most of the catalysts suffered the problem of different types of undesirable alcohols as opposed to only higher alcohol which is desired product of the process. That is why novel catalytic synthesis techniques are an active area of research in this area.

Hydrogen production from the gasification of palm oil biomass is one of the most sought after technologies in this domain. Supercritical water gasification technology is amongst the latest gasification techniques to produce hydrogen. The cost of hydrogen production from supercritical water gasification is reported to be the least amongst the different pyrolysis and gasification technologies since it utilizes high moisture content biomass without the expensive pre-processing (Matsumura, 2002; Shuit et al., 2009). The process, however, produces fermentation sludge which is difficult to deal with. Nevertheless, there are still lots of room for improving the overall efficiency of this process.

Table 3.
Overview of pyrolysis technologies for palm oil biomass.

Reactor Type	Catalyst Used	Pretreatment of Biomass	Biomass Used	Yield of Bio-oil	Reference
Fixed and stirred bed	-	-	Oil palm shell	-	Salema and Ani (2011)
Fixed bed reactor	-	Acid washed red mud with biomass	Empty fruit bunch	52%	Lim et al. (2014)
Fixed bed reactor	Catalyzed by minerals in biomass itself	-	Empty Fruit Bunch (EFB), Palm Kernel Shell (PKS), Palm Meso carp Fiber (PMF)	58.2 % for EFB, 49.8% for PKS and 53.1% for PMF	Asadieraghi and Daud (2015)
Fixed bed reactor	-	-	Trunk, Frond, palm leaf and palm leaf rib	40.87% (Trunk), 43.50% (Frond), 16.58% (Palm leaf) and Palm leaf rib (29.02%)	Abnisa et al. (2011)
Fluidized bed reactor	-	Grinding, sieving and oven-drying of biomass	Oil palm shell	58% (at 500 °C)	Islam et al. (1999)
Turbular reactor	-	Grinded and screened	Palm shell waste	46.40%	Abnisa et al. (2011)

3.2.2. Gasification

Gasification as opposed to pyrolysis occurs in the presence of oxygen and under high temperatures in the range of 800-1300 °C. Unlike pyrolysis, the oxidation of biomass results in gaseous and solid products such as charcoal, water gas, and CO_2 (Geng, 2013). Gasification process has several advantages such as high thermal efficiency, availability of well developed equipment, and reduced emissions. However, the process has some drawbacks which need to be addressed in order to improve the biofuel yield. Minimizing energy content and improving reactor design are key areas which require further attention of the researchers in this field.

As far as the palm oil industry is concerned, biomass from all sources such as EFB, PKS, PMF, fronds, leaves, etc. can be burned in a gasifier to produce

3.2.3. Other Technologies

Besides pyrolysis and gasification, there are other thermochemical, physical and biological technologies which can be employed to utilize the biomass. Torrefaction in conjunction with gasification or co-firing can improve the process yield from palm oil biomass significantly. Torrefaction is a slow roasting process carried out at 200-300 °C which destroys the fibrous structure of the biomass while enhancing its calorific value (van der Stelt et al., 2011; Sabil et al., 2013). The torrefaction process efficiency is a strong function of chemical composition of the biomass and decomposition temperature. Torrefaction, although enhances the overall yield of the energy conversion process, comes with economic

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disadvantages as it increases the overall cost of the biomass pretreatment process.

Bioconversion methods involve the break-down of cellulose and hemicellulose structure of the biomass into fermentable sugars using enzymes. This 'enzymatic hydrolysis' process is followed by fermentation which produces bioethanol, biogas, and biobutanol. Numerous studies have investigated different pretreatment methods, such as acid/alkali, steam, etc., for enhancing the digestibility of the EFB biomass (Han et al., 2011; Jung et al., 2011; Shamsudin et al., 2012). The results have shown considerable improvements in overall yield of useful products such as bioethanol. Although the bioconversion process is less energy intensive as opposed to the thermochemical energy conversion processes, however, the process yield is significantly less compared with the pyrolysis and gasification methods. That is why it has still a long way to go in terms of large scale production of biofuels.

Another method to utilize the energy of palm oil biomass is by compacting the high energy content areas of biomass through physical processes. It has been reported that the densification of the biomass enhances the material handling and combustion property. The EFB biomass in terms of dust and powder can be transformed into briquettes under high pressure and temperature. Several studies have reported the mechanical and combustion properties of the briquettes and pellets made from such biomass (Husain et al., 2002; Nasrin et al., 2008). This method however, has less energy conversion efficiency as opposed to thermochemical and bioconversion methods.

3.2.4 Future prospects of oil palm biomass conversion technologies

Moisture content plays an important role in determining the energy conversion process to be used. Higher moisture content favours the use of biochemical methods such as fermentation and enzymatic hydrolysis. However, if the moisture content is lower, thermochemical methods such as pyrolysis will be more suitable for the biomass (Asadieraghi and Daud, 2015).

Thermochemical conversion of oil palm biomass is still a developing area which has a lot of room for improvements in terms of pretreatment of oil palm biomass, reactor technology for biooil production, catalytic upgrading of the resultant biooil, and hydrogen production. Although some novel approaches such as microwave-induced pyrolysis and plasma-induced pyrolysis/gasification have been introduced (Wan et al., 2009; Salema and Ani, 2011; Salema and Ani, 2012), however, their yields are yet to become competitive with those of the traditional gasification and pyrolysis processes executed through conventional methods. Also the moisture and oxygen contents present in the bio-oil lower its heating value. This problem can be addressed by refining the catalytic cracking process through reactor design and improved catalyst synthesis.

Plasma-induced gasification is a novel technique to utilize the solid waste from palm oil in an environmentally-friendly manner. Standard gasification operates at a lower temperature and produces tars and other contaminants which need to be removed. Plasma-induced gasification on the other hand converts most of the carbon into fuel since it uses an external heat source resulting in little combustion (Mountouris et al., 2006). It should be mentioned that although this technique is not currently being employed for gasification of palm oil biomass, the authors believe that this technology is worth investigating for energy conversion of oil palm biomass. Furthermore, the use of renewable resources to synthesize catalysts for the pyrolysis and gasification reactions which can enhance the regeneration of the catalysts is also a potential area of future investigations in this area.

4. Life cycle assessment and technoeconomics aspects

In recent years, the sustainability issue almost in all sectors has received a lot of attention worldwide. The terms "sustainability" and "sustainable development" have been defined in different ways by different researchers. Although sustainability can cover several aspects, the important goals are to minimize the use of natural resources, production of toxic materials, emissions of hazardous pollutants, and to improve energy efficiency, economic growth, and social standards. Environmental sustainability assessment, which involves evaluating major environmental impacts of a production process throughout the life cycle of the product is carried out using different tools, one commonly used tool is life cycle assessment or analysis (LCA). It is an environmental assessment tool used to evaluate and quantify the impacts of a product over its life cycle (which includes extraction of raw material, processing, product supply, recycling, etc). The acceptance and reliability of the LCA depends on several factors among which the important one is the selection of the system boundary which defines which production processes are included in or excluded from the analysis.

As pointed out earlier, biofuels do have a main impact on food security, water quality, biodiversity, and the environment. The extent of these impacts depends on what raw materials are selected for biofuel production, the plantation and harvesting of the raw material, the synthesis route, and the methods used to supply the produced biofuels. More information on the sustainability and its importance in the biofuel sector could be found elsewhere (Lee and Ofori-Boateng, 2013). There are a number of studies carried out to understand the sustainability of palm-based biofuels produced using a variety of raw materials and synthesis routes. Some researchers have also compared the sustainability of palm-based biofuels with those obtained using other raw materials. This section discusses selected sustainability studies on oil palm biofuels mainly using LCA tools.

Mukherjee and Sovacool (2014) provided a concise review of palm-oil based biofuels in Indonesia, Malaysia, and Thailand as well as also some information on the sustainability implications of palm-oil based biofuels in the Southeast Asia region. The review provides a detailed analysis of the environmental, ecological and socio-economic considerations. They finally recommended three policies which include implementation of standards for oil palm plantation to address the environmental sustainability, recognition and revision of the traditional land use rights and support, and finally, encouragement for the development of new biofuel technologies that uses different feedstock with improved energy efficiency of processes to avoid sole dependence on palm oil-based biofuels. Chiew and Shimada (2013) carried out an interesting study on the environmental impacts of utilizing oil palm EFBs for various applications such as fuel, fiber, and fertilizer. They reported that the technology with the least emissions was composting while the emissions associated with fuel production was comparatively higher. However, they reported that the most favourable technology based on the product was combined heat and power system (Chiew and Shimada, 2013). Johari et al. (2015) in their review pointed out the challenges and prospects of palm oil-based biodiesel in Malaysia. The production sustainability was highlighted as one of the most important factors in the use of palm oil based biofuel. They did conclude that further research is needed to improve the sustainability of biodiesel and to improve the socioeconomic aspects of Malaysian biodiesel.

Yusoff and Hansen (2007) investigated the feasibility of performing LCA on crude palm oil production. Their LCA analysis included three steps of plantation, transportation, and milling of biomass as the most significant steps according to the authors. Based on their analysis and the eco-indicators calculated, they pointed out that the most important aspect concerning the environmental impact was the way the land was prepared for plantation, i.e., burning used as the easiest way which. The transportation and milling also had considerable impacts on the environment, less severe than the plantation though. Yusoff and Hansen (2007) also provided suggestions to improve the sustainability of the palm oil industry such as compulsory use of LCA tool for environment assessment, incentives for introduction of cleaner technologird, and execuation of the LCA on plantation land use in Malaysia. In a different study, Peng (2015) carried out a comparison of the exhaust emissions using three types of biodiesels with the pure petro-diesel fuel. This experimental study was carried out using a water cooled diesel engine. The results showed the fuel consumption was higher for all biodiesels compared with the petro-diesel. However, the CO, hydrocarbons, and smoke emissions were much lower for all the biodiesels compared with petro-diesel.

Although the palm based biodiesel is mainly produced in the Southeast Asia region, there are a number of research articles providing a perspective on the other oil-palm growing countries such as Brazil. Queiroz et al. (2012) carried out the LCA of palm oil biodiesel in the Amazon. The analysis was carried out for the three phases of plantation, oil production, and biodiesel production using transesterification reaction.

Based on their energy performance study, it was suggested that all the three phases could be potentially improved. The most energy intensive phase was found to be the plantation. This observation was similar to what reported by the other researchers. For instance, de Souza et al. (2010) also carried out greenhouse gas (GHG) emission study of palm oil biofuel and also concluded the agriculture (plantation) to be the phase with the highest GHG emissions.

On the other hand, it has been reported that the palm-oil based biofuels produced using the traditional processes are not acceptable because of the certain unfavourable properties such as high viscosity. There have been several attempts to improve such properties; one of them was the use of microemulsion fuels. It has been reported that the microemulsion based biofuels had favourable combustion performance compared to petro-fuels resulting in lower exhaust emissions (Arpornpong et al., 2015). Arpornpong et al. (2015) carried out a comparative LCA study of microencapsulation-based biofuel produced from palm oil-diesel blends with ethanol with neat biodiesel and biodiesel-diesel blend. The LCA analysis was divided into five stages which included cultivation, palm oil production, microemulsion stage, transportation, and exhaust emissions of the fuel application stage. It was found that the microemulsion fuel production had the lowest impact on the environment except in terms of land use and fossil depletion which were mainly the results of the use of surfactant for microemulsion. Another alternative method used was biodiesel production in supercritical alcohols as it has been found to generate only a traceable amount of waste and pure glycerol as a by-product; the details can be found elsewhere (de Boer and Bahri, 2011). Sawangkeaw et al. (2012) studied another novel process with supercritical alcohols using Hysys simulations and carried out the LCA analysis. It was shown that the novel process which was carried out at higher temperature (400 °C) than the previously-proposed biodiesel production in supercritical alcohols (carried out at 300 °C) generated lower environmental impacts.

In general the LCA analysis of palm-oil based biofuels obtained using various feedstock and processing routes suggest that the highest environmental impacts are attributed to the plantation stage.

5. Research and development needs

As discussed in the introduction section, the use of renewable fuels received a lot of attention in recent years for several reasons. The previous sections also provided information on the importance of oil palm and palm oil processing wastes in biofuel production while explaining several recent technologies for production of biofuel from oil palm-based raw materials. However, there are certain challenges which also provide opportunities for further research and development in this area.

A rapid depletion of crude oil reserves and fluctuating oil prices were always important reasons for adoption of other fuel options such as biofuels. However, considering the recent trends in oil prices (a continuous decrease in the oil prices from USD 105 per barrel in August 2014 to USD 25 per barrel in February 2016), it is difficult to justify the use of biofuel solely based on the cost considerations. Johari et al. (2015) showed that for palm biodiesel to breakeven, the crude oil price must be around USD 100 per barrel. Therefore, it will be challenging to come up with cost effective production routes for biofuels to compete with this reverse trend in the crude oil prices. The choice of feed is also important for the success of biofuel production as the price of biofuel is significantly affected by the cost of raw materials.

On the other hand, as discussed in the previous section, the use of oil palm and palm wastes for production of biofuels has a long term effect on the environment. It has been reported by several researchers that the use of palm feedstock for biofuel can result in several impacts on biodiversity as well. Therefore, A number of measures have to be taken especially about the plantation phase in the palm-based biodiesel production cycle. In line with that, detailed LCA analyses can provide useful information for the governments to take the necessary actions.

The sustainability analysis of the various production routes for palm-based biodiesel also shows that there is a need for more research and innovative ideas in order to reduce the environmental impacts and reduce energy consumption. The improvement of processes is also needed in order to produce biofuels with certain properties which are more compatible with the existing diesel engines, especially the properties such as viscosity, cetane number, and calorific value.

6. Concluding remarks

Production of biofuel from biomass wastes has received considerable attention worldwide amid the efforts to find alternative sustainable and environmently-friendly energy resources. Among the sources of biomass, palm oil industry is one promising source as it generates a huge quantity of biomass residues which are currently underutilized. Despite the efforts devoted to maximizing the utilization of biomass potentials in oil palm plantations and mills, the progress is slow. This slow development is mainly attributed to the remote location of palm oil plantations and mills making it difficult to transport and distribute the products (electricity, biogas, and biofuels) or the feedstock to produce biofuels from the plantation to the end-user. On the other hand, the main issue in utilizing the palm oil wastes to produce biofuels, is the unavailability of dedicated pipelines to collect the waste cooking oil.

On the production technology, various processes have been developed and evaluated in producing biofuels from palm oil and oil palm wastes. In general, these technologies can be classified into liquid processing technologies and solid processing technologies. The main issue with the current biofuel production scenario from palm oil wastes is the high moisture content limiting the energy conversion efficiency of thermochemical methods. Should the moisture content be lowered (by an energy efficient drying method), thermochemical methods such as pyrolysis/gasification can be applied effectively. One issue in the utilization of pyrolysis/gasification method is that these methods produce tars and other contaminants which need to be removed. Therefore, some novel thermochemical conversion techniques have been proposed and evaluated such as microwave-induced pyrolisis and plasma-induced pyrolysis. The later, for example, converts most of the carbon into fuel since it uses an external heat source which results in little combustion. These technologies, however, require further investigations prior to their utilization in real life.

On top of the potentials and technologies of biofuel production from oil palm and palm oil wastes, LCA studies have been conducted to evaluate the sustainability aspects of the different scenarios, i.e., biofuels produced using a variety of raw materials and synthesis routes. These analyses revealed that in producing biofuel from oil palm and palm oil wastes, the plantation phase has the highest environmental impacts.

Finally, with the current drop of oil price, it is difficult to justify the use of biofuel solely based on the cost considerations. More specifically, it will be difficult to design cost effective production routes for biofuels to contend the current low prices of fossil fuels. Hence, more studies are required to (i) develop an efficient transport and distribution system to connect plantation, biofuel plants, and end users, (ii) design an efficient conversion method to produce biofuel which has no or minimum impacts on the environment, and (iii) implement the improvement gained from the LCA studies with the main goal to develop cost-effective, environmentally-friendly and profitable biofuel production from oil palm wastes.

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