Performance evaluation of biodiesel from used domestic waste oils: A review

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ABSTRACT

Global warming, high-energy demand and availability of new technologies are among the factors catalyzing the search for alternative sources of energy. Currently, there is renewed interest in obtaining energy from wastes hitherto meant for disposal. Increased costs of disposal and their attendant problems of heavy environmental loading are some aspects making the disposal option unattractive. These wastes are sources of energy and among the several sources of generating this energy are the waste-to-energy (WTE) categories with potentials for useable fuel production. The WTE materials are mainly used domestic waste oils (UDWOs), municipal solid waste (MSW), agricultural and industrial wastes. However, the latter wastes are not attractive as they consist of innumerable hazardous contaminants. The UDWOs are arguably a safe and cost effective source of useable fuel. Their conversion offers the merits of a reduction in greenhouse gas emission (GHG), enhancing fuel diversification and a qualitatively comparable energy output to fossil diesel fuels. Thus, UDWOs could significantly contribute towards achieving the 2020 and 2030 goals of substituting approximately 20% and 30% of petro-diesel with biofuels in US and EU, respectively. Moreover, attaining the forecasted annual production rate of 227 billion liters of biofuel by most active stakeholders in the biodiesel industry could be easily achieved.

This review aims to analyze the performance of biodiesel fuels obtained from UDWO and to demonstrate the suitability of applying these fuels as substitutes to mineral diesel in various industries. Benefits of UDWO as a biodiesel feedstock were as well highlighted.

Keywords: Biodiesel; Biodiesel feedstock; Used domestic waste oil; Waste treatment

1. Introduction

The generation of waste and their significant environmental consequences has been described to have risen in the past decades due to the rapid industrialization and its associated impact upon the world economy (Tsai and Chou, 2004). The proper management of waste not only contributes significantly to reducing the numerous adverse effects on public health (Fabiyi and Skelton, 1999; Winward et al., 2008) but also has a major impact upon lowering global warming effects (Papageorgiou et al., 2009). The latter problem has been identified as the most critical environmental issue currently (Ahmad et al., 2011). Among the detrimental effects of global warming are loss of lives, extinction of species and submerging of islands arising from a rise in sea levels (Ahmad et al., 2011).

Recently, there has been a lot of clamours regarding the environment and its sustainability (Felizardo et al., 2006; Papageorgiou et al., 2009). Thus UDWO should be considered as a source of fuel for effective mitigation of greenhouse gas emissions (GHG) as well as for providing environmental benefits and sustainable development via waste conversion to energy (Papageorgiou et al., 2009). Still on attaining sustainability, and in line with the objective of achieving the 2020 and 2030 goal of substituting approximately 20% and 30% of

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petro-diesel with biofuels in US and EU, respectively (González Gómez et al., 2002), a policy of recovering value from waste has been enforced and this includes waste diversion from landfill. The interest of the European Union in the utilization and consumption of biodiesel is based on its greater production of biodiesel, which is estimated at approximately 85% of the world’s total (3.8 billion liters in 2005) (Ahmad et al., 2011).

Energy from waste has been described by Papageorgiou et al. (2009) as a waste management option that could significantly reduce greenhouse gas emissions (GHG). For used domestic waste oil (UDWO), the current world annual figure of UDWO generation is estimated to be more than 15 million tons (Kalam et al., 2011). This waste is channeled through the drain with the related implications of energy loss and inhibiting performance of municipal wastewater treatment plants (Felizardo et al., 2006). These reasons among others results in the prohibition of dumping domestic wastes in municipal waste treatment facilities. Thus, these wastes, if effectively treated are a potential source of an ecologically friendly fuel (Cvengros and Cvengrosová, 2004).

The interest of this study is limited to wastes with potentials of being converted to fuels and specifically to methyl esters (MEs) of long fatty acids (biodiesel). The performance of the biofuel is adjudged to be comparable to fossil fuels (Felizardo et al., 2006) and its use in the compression-ignition (CI) engine requires little or no modification of the engines themselves (Çetinkaya et al., 2005). Biodiesel is also an environmentally friendlier form of fuel. Being renewable it offers the merit of reduction in greenhouse gas emissions while the UDWO is available everywhere. Moreover, indicators show that sources of fossil energy are rapidly depleted, and the future forecast is not encouraging. Thus biodiesel could go a long way in attaining the 2020 and 2030 target by several key players in the globe. For instance, the US plans to replace the utilization of both diesel and petrol with biofuels by 30% (2030) and similarly EU member countries have planned a 20% substitution of fossil fuel by 2020 in the transportation sector. This necessitates adopting policies by all of the most active players in the industry, i.e. the European Union, China, Australia and New Zealand, aimed at increasing production. Currently, the annual biofuel production target is approximately 277 billion liters (Blake et al., 2008).

The objectives of this review are to give an overview of potential sources of feedstock for biodiesel production, their merits and demerits, and the environmental incentives for promoting biofuel generation from such sources. The benefit analysis in using UDWO as a fuel source is further discussed. The summary of the findings clearly indicates several merits in the generation of biodiesel from UDWO, an energy source yet to be fully exploited. The research findings further establish the need to harness UDWO for mass-scale biodiesel production.

2. Biodiesel

2.1. Definition

Biodiesel can be defined as a monoalkyl ester of long chain fatty acids derived from a renewable lipid feedstock, such as vegetable oil or animal fat.

2.2. History

A succinct history of biodiesel has been provided in a separate review paper (Lin et al., 2011a). Biodiesel production from vegetable oils was first conducted by Duffy and Patrick in 1853. In 1893 vegetable oils were used for the first time in a CI engine by Rudolf Diesel. By 1920s, due to the relative cost effectiveness, availability and government subsidies, fossil-based diesel application completely over took the vegetable oils. Due to problems arising from poor atomization of the fuel that resulted in deposition of residues and coking of the injectors, combustion chamber and valves, the vegetable oils needed refining by processes such as pyrolysis (Mahfud et al., 2007), blending (Fontaras et al., 2007; Pramanik, 2003) and microemulsification (Srivastava and Prasad, 2000). However, problems were observed to persist especially with carbon deposition and contamination (Gerpen, 2005; Sarin et al., 2007). Hence, conversion of vegetable oils to biodiesel using transesterification grew in popularity.

To ensure proper quality control of the fuel various biodiesel standards, such as EN 14214 (Europe) and ASTM D 6751 (North America), were formulated. Adherence to these standards make it easier for automobile manufacturers to issue engine warranties for the implementation of biodiesel fuel in the engine (Lin et al., 2011a). Continuous revision and updates of the standards became necessary as automobile manufacturers evolved newer engine designs with the passage of time. As a consequence of strict quality control on biodiesel fuel, service outlets started frequenting many parts of Europe and US during the 2000s. However, the cost of biodiesel fuel has limited its widespread commercialization and various research and development programs are ongoing throughout the globe to bring the cost factor down (Chuepeng and Komintarachat, 2009; Lin et al., 2011a). Thus, identifying cheaper and sustainable sources would always be a welcome progress.

3. Potential biodiesel feedstock sources

The need to examine and harness potential feedstock for biodiesel production is hinged on the fact that the petro-diesel sources are associated with plenty of problems. They range from possible depletion of the fossil fuel sources (estimated at 41 years) (Agarwal, 2007) to adverse effects on the environment as a consequence of their utilization (Ahmad et al., 2011). In fact, a major problem that arises from the exploration and consumption of the fossil based fuels is the steady decline in underground-based carbon fuel reserves (Melvin Jose et al., 2011).

There are many potential sources for biodiesel production from biomass. By definition, biomass includes all biodegradable fractions of products, waste and residues from agriculture (vegetable and animal substance), forestry and related industries and the biodegradable components of industrial and municipal waste (Chuepeng and Komintarachat, 2009). Some of these sources would be briefly analyzed in the proceeding sections.

For feedstock of forestry origin, many socio-economic and environmental issues adversely affect the large scale exploitation of this form of resources for biodiesel production. Among others are policies involved in primary forest destruction, issues with non-governmental organizations (NGO),
displacement of natural habitat and conflict with the indigenous population (GFOM, 2007).

The high cost of biodiesel is incurred in the form of feedstock cost, which ranges from 70 to 95% of total operating costs. A limit of 75% for the cost of raw materials has also been reported (Ahmad et al., 2011; Chuepeng and Komintarachat, 2009; Lim and Teong, 2010) and illustrated graphically in Fig. 1. This higher production cost necessitates the search for more economically attractive feedstock which, via their utilization, effectively lowers the production cost (Ahmad et al., 2011).

3.1. Industrial

These categories of waste are known to be the most problematic of all the wastes disposed/generated. This is associated with their great complexity and serious environmental hazards (Fabiyi and Skelton, 1999;Pidou et al., 2009; Tsai, 2010). They are an unattractive source of generating energy as they are known to contain toxic contaminants in quantities sufficient for adversely affecting the environment and quality of life. Equally, non-hazardous waste is generated from sources such as food processing waste, scrap plastics, waste rubber, waste paper, organic/inorganic sludges, coal ash and others (Tsai, 2010). However, most of these wastes are non-biodegradable in nature. Thus, they lack the potentials for biodiesel production as they fail to meet the “biodiesel from biomass” criteria. On the other hand, there are industrial discharges of wastes that are non-hazardous in nature and have potentials for biodiesel generation, especially from the palm oil industry. Among such are palm oil fatty distillates (Hayyan et al., 2011), tobacco seed oil (Usta et al., 2011), rubber seed oil (Melvin Jose et al., 2011) and low grade oils such as sludge palm oil (Hayyan et al., 2011). Again, issues of sustainability of some of these sources become their bane.

A sustainable source is the use of waste generated from crude vegetable oil discoloration (bleaching). Reported work in the literature suggests that the utilization of the adsorbed crude vegetable oil on the spent bleaching earth (SBE) is an economical approach. These residual oils recovered from the SBE are a potential biodiesel feedstock source. The SBE oils, mostly generated from soybean, rapeseed and palm oil refinery facilities have similar composition to vegetable oils (Pizarro and Park, 2003; Loh et al., 2006; Huang and Chang, 2010).

As the SBE is directly sourced from edible oil, the sustainability of this form of feedstock is assured, thus, based on figures reported by Huang and Chang (2010) of 1.2–1.6 kg of SBE generation per metric ton of edible oil production, an average of 1.5–2.0 million tons of biodiesel are generated from the edible oil production of 128.2 million metric tons.

In addition, the percentage yields of residual oils recovered ranges between 20 and 40% of residual oil from SBE (Loh et al., 2006; add). This coupled with the high conversion yield of the extracted oil make its utilization attractive. There are several routes for the methyl esters conversion. The lowest conversion is obtained in the case of methanolysis, such as the use of lipase-catalyzed method as reported by Pizarro and Park (2003) where a conversion of 55% (w/w) is attained. However, as lipase catalyzed transesterification is expensive compared to other methods, it is not very economical to produce biodiesel using this reaction (Marchetti et al., 2005; Boey et al., 2011).

A higher conversion of 75.2% is reported when the in situ transesterification is supplemented by means of ultrasonification using petroleum ether (PE) as an organic co-solvent (Boey et al., 2011). The higher yield may be associated with induced asymmetric cavitation bubbles collapse at the oil/alcohol boundary which enhances the mass transfer between the phases thus accelerating the reaction (Boey et al., 2011). A slightly higher conversion of 80% (Table 1) is obtained when solvent and supercritical-fluid (SC-CO2) extraction are employed (Loh et al., 2006). Of the many conversion approaches, the two-step esterification reported by Huang and Chang (2010) gave the highest yield of 85–90%.

The quality of biodiesel derived from residual oil of SBE is in reasonable agreement with both EN 14214 and ASTM D6751 standards and have comparable fuel properties as petroleum diesel. Hence, these methyl esters may be used as a diesel substitute (Huang and Chang, 2010).

Moreover, as disposal of the SBE poses serious environmental hazards associated with fire and pollution (Huang and Chang, 2010; Boey et al., 2011), the oil extraction becomes a sound alternative to its disposal. In addition, the oils extracted exhibit poor qualities in terms of free fatty acids (FFA) content of more than 10% along with high peroxide values (Loh et al., 2006) thus making them suitable for food applications. In addition the de-oiled bleaching earth can be reused as an adsorbent in wastewater treatment or as a clay substitute in the brick or tile manufacturing process (Boey et al., 2011).

3.2. Agricultural

Production of biodiesel from agricultural, non-food feedstock sources is another viable option that potentially reduces the utilization of edible oils. Such crops that have been reportedly used includes: rubber seed (Melvin Jose et al., 2011; No, 2011), jatropha (Jain and Sharma, 2010; Juan et al., 2011; No, 2011), mahua (Saravana et al., 2010), tobacco seed (Usta et al., 2011), castor (Chakrabarti and Ahmad, 2008), erucic sativa (Chakrabarti and Ahmad, 2009) and pongame (Kumar and Sharma, 2011), among others. It could be argued that these sources of biodiesel feedstock have minimal effect on the competition for food and that some species are adaptable to growth on wastelands (Ahmad et al., 2011). However, the viscosity of neat vegetable oil (range of 28–40 mm²/s) is high; its direct use has led to diesel engine problems such as deposits formation and injector coking arising from poor atomization (Knothe, 2010).

Of interest is Jatropha curcas oil, as it comprises non-edible oil, coming from a perennial plant, with high oil content in the seed and with good productivity per hectare (Zanette et al., 2011). Most recent experimental studies on this oil have been conducted by Zanette et al. (2011). In their study new
experimental data and kinetic modeling of transesterification of *Jatropha curcas* oil are reported using heterogeneous catalysts. The results show that by using KSF clay and Amberlyst 15 as catalysts around 70 wt.% of FAME yield are obtained at relatively mild conditions and short reaction times. However, catalyst inactivation during re-use has been found to occur. Thus for large-scale production the technical limitations need to be addressed. Moreover, this feedstock availability is more in Africa and India (Table 2). Accordingly, for EU’s utilization of *Jatropha curcas* importation factors comes in. From an economic point of view, this is unattractive and contributes to the figures reported by Predojevic (2008) in which vegetable oil derived biodiesel costs amount to about 10–50% higher than that of petroleum-based diesel fuel.

To attain the biodiesel production target using rapeseed (the main European feedstock), about 60% of Europe’s arable land has to be utilized. Based on this figure it is clear that the target cannot be met (GFOM, 2007). Even the previous targeted quota (2010 EU’s target of replacing 5.75% of diesel fuel with biofuel), which appears small translates to very large scales in practice. Still, on these figures, Skelton (2007), has highlighted the scenario involved in attaining the previous 2010 EU’s target of replacing 5.75% of diesel fuel with biofuel to include competition with food crops and the destruction of rain forests at the expense of new plantations. For palm oil, a report raised by Marcel Silvanus (GFOM, 2007) has shown that as a sustainable source the use of palm oil is unattractive from an environmental perspective. This is based on the release of massive amounts of carbon dioxide, and the oil is far from being carbon-neutral. Although, several articles have questioned the credibility of the data generated and subsequent analysis, the fact is that in Europe several calls have been made for banning its use.

### 3.3. Municipal

The production of biodiesel from municipal sources, which includes animal fat and beef tallow, has been well documented in many referenced literature (Liu et al., 2011; Ma et al., 1999; Nelson and Schrock, 2006; Soldi et al., 2005; Zheng and Hanna, 1996). It offers the merit of being a cheap form of alternative renewable energy source to petroleum fuel. Generally, they are classified into mainly edible and inedible types and are generated by the meat packing, poultry, and edible/inedible rendering industries (Nelson and Schrock, 2006). Technically, the use of this feedstock as a biodiesel source presents difficulties in terms of production. They contain a high amount of saturated fatty acids (SFA) which leads to a difficult esterification process. A typical example is beef tallow with an average SFA representing approximately 50% of the total FA, thus accounting for high melting point and high viscosity of the final biodiesel. Additionally, bio-safety consideration is another factor limiting the viability of such sources as contaminated animals are not discriminated in the fat application (Ahmad et al., 2011).

#### 3.4. Used domestic waste oils (UDW0)

Literature is replete with studies on UDWO for biodiesel production. Among the several sources are cottonseed oil, soybean oil, sunflower oil, tobacco seed, and palm oil (Dorado et al., 2003; Hamasaki et al., 2001; Phan and Phan, 2008; Tashtoush et al., 2003; Wu et al., 2009). The UDWO is a more attractive low-cost feedstock for biodiesel production in comparison to vegetable oils as they are not affected by land policies as witnessed in some countries, especially the EU (González Gómez et al., 2002), price is half that of vegetable oil and huge amounts are generated (approximately 0.4 Mt from EU countries while estimated amounts stand at 0.7–1.0 Mt) (González Gómez et al., 2002). In a recent review by Zanette et al. (2011), several advantages of UDWO have been highlighted, and these include a decrease in the competition with food items, overcoming problems associated with planting and harvesting, a minimum or negligible land area requirement, minimum use of fertilizers, and other factors, which result in the significant decrease in the price of feedstock. A detailed breakdown of feedstock statistics is given by Ahmad et al. (2011) for each of the major producers of biodiesel.

The detrimental effect in employing UDWO to prepare feeding formulations for domestic animals have resulted in its ban in the EU from 2002 (Cvengros and Cvengros ová, 2004). This provides further justification for the necessity of
enlarging UDWO conversion to biodiesel. In comparison to beef tallow, the UDWO applications are limited whereby the inedible form of the former finds usefulness among others as an additive for animal feed, use in fatty acids and soap manufacture, lubricants and others (Nelson and Schrock, 2006). Moreover, the use of waste oils for biodiesel production saves cost significantly as it is almost free or usually priced at a value that is approximately 60% lower than that of conventional vegetable oils (Predojevic, 2008).

It should be noted that in choosing a particular biomass source for renewable energy production, the GHG emission generated in the course of its production, transportation and processing should be factored in. A final check of all the mentioned points might indicate the sources as not so attractive. However, an overall assessment of UDWO clearly shows it is not affected by these limitations.

4. Used domestic waste oil (UDWO)

4.1. Generation

These categories of waste oil are mostly generated from edible vegetable matter. Of all the available sources of domestic waste, used domestic waste oils (UDWO) are arguably the most widely generated. This could be associated with the recent proliferation of fast food outlets (on a small and industrial scale) due to the affinity of the young generation to fast food (Cvengros and Cvengrosová, 2004). Merits of these wastes include less separation and purification steps. Here, pretreatment is basically water and gum filtration, followed by hydrogenation and then de-acidification (Kalam et al., 2011).

The frying process exposes the oil during cooking and the food preparation step renders the oil detrimental to further human consumption (Kalam et al., 2011). Moreover, biodiesel production with UDWO is more universal as fast food outlets are abundant in most urban places while the use of refined edible/non edible oils are restricted to certain countries and regions. This is further buttressed by the amount of UDWO generated from some countries (Table 3). Based on Table 3, it is clearly evident that disposal of these large amounts of UDWO through direct discharges into drains or sewers may lead to significant environmental problems as watercourses and wildlife are directly affected (Kalam et al., 2011).

4.2. Process of frying

Basically, the process of frying involves heating of the vegetable oils for varied times in the air at temperatures ranging from 160 to 200 °C (Cvengros and Cvengrosová, 2004). This in turn degrades the oils through hydrolytic, oxidation and cracking reactions resulting in increased viscosity and acidity as well as associated unpleasant odor and a darker coloration. The variation of treatment conditions and the fact that the oils are sourced from different vegetable oils results in an increased variability in the compositional characteristics of the biodiesel formed from UDWO and accounts for the changes in the chemical and physical properties (Felizardo et al., 2006). The same has been highlighted by Knothe and Steidley (2009).

The detailed analysis of the transformations steps is reported by Cvengros and Cvengrosová (2004). The process may be summarized as the hydrolytic splitting of triglycerides in the presence of water. Although, a portion of the water evaporates, others dissolve in the fat and induce the cleavage to give rise to higher FA and glycerol content. Oxygen dissolves in the fat and initiates the formation of several oxidation products from the reaction of oxygen with unsaturated acyglycerols. The remainder of the fat in the fried oils, constitute the high free fatty acid content that necessitates an additional step – acid pre-treatment, for adequate high-yield conversion to biodiesel (Canakci and Van Gerpen, 2001; Knothe and Steidley, 2009).

4.3. Effect of UDWO properties on the transesterification reaction

Generally, the physical and chemical characteristics of UDWO are associated with contaminants such as water, free fatty acids; these impurities are subject to the fresh cooking oil and are a cause of concern on the quality of UDWO (Gui et al., 2008; Leung and Guo, 2006; Singh and Singh, 2010; Upham et al., 2009). The transesterification process of UDWO is greatly affected by the following parameters: acid value, iodine value and water content. Thus UDWO feedstock needs to be screened for these three parameters (Math et al., 2010). As described by Tsai et al. (2007), the relevance of the analysis is informed by the fact that the free fatty acids content is reflected by the acid value, which can be saponified with caustic catalyst to form saponifiable matter. High water content, on the other hand, manifest negatively on the downstream processing due to the formation of bulk solids in alkali-catalyzed processes. For unsaturated fatty acid measurements, the iodine value is used. This parameter decreases as the deterioration in the edible oil quality increases. For UDWO with low acid value, the transesterification reaction could be performed directly. Similar reports are abundant in the literature, i.e., Canakci et al. (2009) have reported the use of UDWO (palm oil) having an acid value of 0.58 mgKOH/g for biodiesel production. In the literature, reported use of strong acidic ion exchange resins is effective in the esterification reaction of the FFA in UDWO. However, loss of the catalytic activity poses a challenge (Lou et al., 2008; Ozbay et al., 2008).

Despite the potential of UDWO in biodiesel production, they have a limitation of high free fatty acid content of 0.5% (Hayyan et al., 2011; Jiménez-López et al., 2011; Ozbay et al., 2008). This requirement apparently retards the prospects of UDWO as its FFA content is usually more than 2 wt.% (Issariyakul et al., 2007; Watanabe et al., 2001; Zhang et al., 2003). Sabudak and Yildiz (2010), attempted to analyze the compliance of several purified biodiesel fuels with the EN 14214 standard; they faced serious challenges in preparing biodiesel from UDWO without acid esterification when FFA values of the UDWO exceeded 2%. This was similar to the

| Table 3 – Used domestic waste oil generation by countries (Kalam et al., 2011; Thamsiírho and Murphy, 2010). |
|----------------|----------------|
| Country | Quantity (million tons/year) |
| China | 4.5 |
| Malaysia | 0.5 |
| United States | 10.0 |
| Taiwan | 0.07 |
| Europe | 0.7–10 |
| Canada | 0.12 |
| Japan | 0.45–0.57 |
| Ireland | 0.153 |
conclusion reported by Kalam et al. (2011), who further reported that for transesterification reaction, the FFA content of the biodiesel should not exceed 1% (Chakrabarti and Ahmad, 2008; Papageorgiou et al., 2009). Although the FFA content from some sources is less than 2%, others are above 5% (Issariyakul et al., 2007). An implication of this is that the homogeneous alkaline transesterification reaction is hindered by the saponification reaction leading to soap formation (Jiménez-López et al., 2011).

Thus, a step can be incorporated to enhance the suitability and viability of these oils. Canakci and Van Gerpen (2001) demonstrated the feasibility of reducing the high FFA values of a UDWO to less than 1% in a two-step pretreatment process. More recently, Hayyan et al. (2011) reduced the FFA content of a sludge palm oil (SPO) from 23.2% to below 2%. However, such elaborate pretreatment procedures increase the general overhead costs.

The problems can be addressed by employing a strong liquid acid catalyst whereby the transesterification process is not significantly affected since the catalyst has reduced sensitivity towards FFA (Kulkarni and Dalai, 2006). In the literature, Sendzikiene et al. (2004) has achieved nearly -50% conversion of UDWO to biodiesel when using 1% homogenous acidic catalyst (H2SO4) at 50 °C, and a similar result has been reported for A-15 heterogeneous catalyst (Ozbay et al., 2008). However, a higher temperature is required, and a slower reaction rate is observed (Ozbay et al., 2008). Use of solid acid catalyst (ion-exchange resins, zeolites, superacids, etc.) is more attractive, as corrosion is prevented (Viviana Silva and Rodrigues, 2006), a high FFA conversion is attained, and a more effective catalyst separation is achieved (Lotero et al., 2005). On the use of solid acid catalyst, Ozbay et al. (2008) has studied the batch esterification of FFA in UDWO using four different ion-exchange resins (Amberlyst-15 (A-15); Amberlyst-35 (A-35); Amberlyst-16 (A-16) and Dowex HCR-W2) by varying the amount of catalyst used (1–2 wt.%) and observed an increase in FFA conversion with an increase in both catalyst amount and reaction temperature. However, reaction duration can be reduced using an acid catalyst than an ion exchange process as demonstrated in the work of Sendzikiene et al. (2004) where complete FFA esterification reaction has been attained in 15 min for the homogeneous catalyst (H2SO4) as against 100 min for Relite CFS (an acidic ion exchange polymeric resin), which was reported by Tesser et al. (2005). It is known that the production route as well as the feedstock affects the biodiesel produced from UDWO (Zhang et al., 2003). More recently, Sabudak and Yildiz (2010), reported that the transesterification of a UDWO having a FFA value of 4.6% by means of an acid base reaction followed by ion-exchange resin purification met the EN 14214 requirements adequately. This research outcome paved the way of utilizing UDWO composing of more than 2% FFA for biodiesel production.

4.4. Quality of fuel

As mentioned by Knothe and Steidley (2009), a major issue with the application of biodiesel is its fuel properties, which inevitably determines its performance. Generally, as with most diesel-range fuels, biodiesel combustion efficiency in an engine is subject to fuel parameters that include viscosity, lubricity, heat of combustion, cetane number (CN), cold flow characteristics, and oxidation stability (Saraf and Thomas, 2007). Biodiesel from UDWO sources have been reported to possess properties similar to fossil fuels. The biodiesel quality is assessed by various agencies in different countries; however, it must comply with either International Biodiesel Standard for Vehicles (EN 14214) or American Society for Testing and Materials (ASTM) standards (ASTM D 6751). The latter standard stipulates 25 parameters but usually a minimum of seven parameters can be used to assess the quality. Based on this, seven parameters (see Table 4) have been used as a basis in this review. Clearly from the results of Table 4, the latter fuel is associated with low viscosity and lower density in comparison to the former. Based on the similarity of the properties, UDWO-fuels are thus more attractive sources of biodiesel feedstock.

Table 4 shows that the UDWO-biodiesel adequately meets the quality indices prescribed by the ASTM and EN-14214 for biodiesel quality. The UDWO based fuels have been shown to have a higher degree of saturation, greater oxidative stability, higher viscosity, higher cetane number as well as higher cloud and pour points than other counterparts (Knothe and Steidley, 2009). However, the latter two properties can adversely affect fuel performance as they can cause poor low-temperature properties. In addition, increased storage time increases the acid and peroxide values, a common phenomenon with biodiesel originating from other sources (Bouaid et al., 2007). Furthermore, the acid value and viscosity are consistently observed to increase with time as established by Knothe and Steidley (2009) due to variation in the extent of oils and fats saturation. It is observed that irrespective of the source and type of the UDWO, the acceptable biodiesel viscosity range of 1.9–6.0 mm²/s (ASTM D6751) is maintained throughout its storage and performance periods. This is expected as the viscosity of the most viscous methyl ester of common fatty acids (stearic acid methyl ester) is slightly below 6.0 mm²/s (Knothe and Steidley, 2009).

Biodiesel production from UDWO is a continuous one due to increasing production of the waste oils from household and industrial places (Felizardo et al., 2006). A drawback to the use of UDWO is its color (dark-brown or even red), odor (unpleasant), increased viscosity of the fat and acidity due to degradation (Felizardo et al., 2006). Furthermore, increased amounts of free fatty acids, decrease in the iodine number, change in the refraction index and increasing tendency of the fat to foam are all associated with the frying process (Cvengros and Cvengrosová, 2004). These chemical and physical changes, resulting from hydrolytic and oxidative reactions have been discussed by several researchers (Cvengros and Cvengrosová, 2004; Enweremadu and Mbarawa, 2009; Felizardo et al., 2006).

The biodiesel produced from UDWO following transesterification reaction may contain impurities such as soap, mono-, di-, tri-glycerides, glycerine, methanol and salts. Thus, the post treatment method becomes vital. Of the several methods, ion-exchange resins have been shown to be particularly useful for high FFA containing feedstock where satisfactory separation of impurities from biodiesel is attained (Berrios and Skelton, 2008; Ozbay et al., 2008).

The high viscosity of the UDWO feedstock necessitates post processing as the transesterification reduces the viscosity but does not meet the required standard at times. On the high viscosity problem, blending about 5% of the UDWO fuel with No. 2 diesel fuel can adequately address carbon deposition, filter plugging, poor atomization of fuel, injector coking and excessive engine wear problems (Kalam et al., 2011). Kalam et al. (2011) used a multi-cylinder diesel engine to compare emission and performance characteristics of palm
Table 4 – Physical and chemical specifications of No. 2 diesel fuel, waste oil and UDWO-biodiesel.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Flash point (°C)</th>
<th>Pour point (°C)</th>
<th>Cloud point (°C)</th>
<th>Kinematic viscosity (at 40 °C, mm²/s)</th>
<th>Density (at 15 °C, g/ml)</th>
<th>FFA (mg KOH/g)</th>
<th>Water content (mg/kg)</th>
<th>Iodine value (g iodine/100 g)</th>
<th>Cetane number</th>
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<tr>
<td>Utlu and Koçak (2008)</td>
<td>72</td>
<td>−20</td>
<td>−15</td>
<td>2.60</td>
<td>0.8370</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&gt;51</td>
</tr>
<tr>
<td>Demirbas (2009)</td>
<td>485</td>
<td>284</td>
<td>–</td>
<td>26.4</td>
<td>0.9240</td>
<td>1.32</td>
<td>0.42</td>
<td>141.5</td>
<td>49</td>
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<tr>
<td>Phan and Phan (2008)</td>
<td>269</td>
<td>8</td>
<td>21.6</td>
<td>30.05</td>
<td>0.9200</td>
<td>2.36</td>
<td>–</td>
<td>13.2</td>
<td>49</td>
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<tr>
<td>Phan and Phan (2008)</td>
<td>276</td>
<td>15</td>
<td>15</td>
<td>33.47</td>
<td>0.9200</td>
<td>1.8</td>
<td>–</td>
<td>12.69</td>
<td>49</td>
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<tr>
<td>Enweremadu and Mbarawa (2009)</td>
<td>171</td>
<td>–</td>
<td>–</td>
<td>4.23</td>
<td>0.8900</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>54</td>
</tr>
<tr>
<td>Enweremadu and Mbarawa (2009)</td>
<td>156</td>
<td>−2.5</td>
<td>3</td>
<td>4.32</td>
<td>0.888</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>52</td>
</tr>
<tr>
<td>Enweremadu and Mbarawa (2009)</td>
<td>0</td>
<td>0</td>
<td>–</td>
<td>0.8737</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>109</td>
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<td>Enweremadu and Mbarawa (2009)</td>
<td>148</td>
<td>−4</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<td>48</td>
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<tr>
<td>Enweremadu and Mbarawa (2009)</td>
<td>130</td>
<td>10</td>
<td>10.7</td>
<td>5.18</td>
<td>0.8872</td>
<td>–</td>
<td>–</td>
<td>47.9</td>
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<tr>
<td>Ozsezen and Canakci (2010)</td>
<td>70.6</td>
<td>–</td>
<td>–</td>
<td>4.401</td>
<td>0.8750</td>
<td>0.15</td>
<td>–</td>
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<td>60.4</td>
</tr>
<tr>
<td>Predojevic (2008)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>4.88</td>
<td>0.8870</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>58.3</td>
</tr>
<tr>
<td>Predojevic (2008)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>4.88</td>
<td>0.8860</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>58.1</td>
</tr>
<tr>
<td>Utlu and Koçak (2008)</td>
<td>156</td>
<td>−2.5</td>
<td>3</td>
<td>4.318</td>
<td>0.8880</td>
<td>–</td>
<td>–</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>Tsai et al. (2007)</td>
<td>180</td>
<td>6</td>
<td>–</td>
<td>4.7116</td>
<td>0.8823</td>
<td>–</td>
<td>–</td>
<td>45.9</td>
<td></td>
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<tr>
<td>Tsai et al. (2007)</td>
<td>173</td>
<td>6</td>
<td>–</td>
<td>4.7568</td>
<td>0.8826</td>
<td>–</td>
<td>–</td>
<td>45.8</td>
<td></td>
</tr>
<tr>
<td>Sabudak and Yildiz (2010)</td>
<td>159</td>
<td>–</td>
<td>–</td>
<td>5.46</td>
<td>0.8860</td>
<td>0.33</td>
<td>381</td>
<td>106</td>
<td></td>
</tr>
<tr>
<td>Sabudak and Yildiz (2010)</td>
<td>161</td>
<td>–</td>
<td>–</td>
<td>5.22</td>
<td>0.8840</td>
<td>0.33</td>
<td>317</td>
<td>106</td>
<td></td>
</tr>
<tr>
<td>Sabudak and Yildiz (2010)</td>
<td>151</td>
<td>–</td>
<td>–</td>
<td>4.63</td>
<td>0.8820</td>
<td>0.23</td>
<td>372</td>
<td>106</td>
<td></td>
</tr>
</tbody>
</table>

* No. 2 diesel fuel.
* Waste oil.
* UDWO biodiesel.
oil and coconut waste cooking oil blends tagged C5 and P5, respectively. They reported, in comparison with No. 2 diesel, lowering of brake power of 0.7% and 1.2% for C5 (blended with 95% diesel) and P5 (blended with 95% diesel), respectively. Generally, using the blended fuels, higher exhaust emission reduction was attained for unburned hydrocarbon (23% and 17%), 7.3% less smoke and a 21% decrease in carbon mono-oxide (CO) content, while increases of 1% and 2% of nitrogen oxides (NOx) were reported for C5 and P5, respectively.

Another factor determining the suitability of biodiesel fuel is its oxidative stability; several researchers have investigated the stability of UDWO biodiesel and found it stable (Knothe et al., 2003; Saraf and Thomas, 2007; Knothe and Steidley, 2009). This stability has been associated with higher saturates ratio in UDWO and also its antioxidants content (Knothe and Steidley, 2009). The role of the degree of unsaturation enhances the reactivity of the fatty acid molecule; as the extent of fatty acid unsaturation increases in a chain it implies an increase in reactive bonds. This results in lowering the cetane number (Knothe et al., 2003) and increases NOx emissions. A consequence of this can result in the promotion of oxidative degradation that may decrease the lubricity of biodiesel and contribute to gum formation in the engine (Saraf and Thomas, 2007).

### 5. Biodiesel testing and evaluation in compression-ignition engines

As highlighted by Skelton (2007), the requirements of current diesel engines are strict with respect to fuel quality. Thus, to obtain a holistic assessment of the fuels’ suitability, it is imperative to analyze the performance of the fuel in CI engines. Merits of biodiesel fuel relative to petro-diesel drive the search for such renewable alternatives. Briefly, the merits could be enumerated as a higher combustion efficiency and cetane number (Demirbas, 1998), a high biodegradability of 90% within 21 days (Speidel et al., 2000), low emission of toxic gases due to lower sulfur and aromatic content (Chakrabarti and Ali, 2009) and appreciable reduction of most exhaust emissions such as monoxide, unburned hydrocarbons, and particulate matter (Chakrabarti and Ali, 2008, 2009; Chakrabarti et al., 2010, 2011). It has been found in various research investigations that the average NOx emission for B20 blends increases by ca. 2% in comparison to petro-diesel and figures of ca. 10%, 11% and 21%, are reported to represent reduction in particular matter, carbon monoxide and total hydrocarbons emissions, respectively (Chakrabarti et al., 2011). This is especially true for biodiesel produced using base catalysts in comparison to the employment of acid catalysts or enzymes (Basha et al., 2009).

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**Table 5 – Findings on biodiesel and blends on internal combustion engine performance.**

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Findings</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of pongamia methyl ester</td>
<td>NOx emissions were lower with retardation of injection timing and exhaust gas recirculation</td>
<td>Basha et al. (2009)</td>
</tr>
<tr>
<td>Emissions of neat and blended rapeseed biodiesel in a diesel engine.</td>
<td>Biodiesel was found to decrease CO, HC and visible emissions while increasing NOx emissions in comparison to diesel fuel.</td>
<td>Labeckas and Slavinskas (2006)</td>
</tr>
<tr>
<td>Jatropha oil effect on injection timing and rate, injector opening pressure and engine air swirl.</td>
<td>Smoke and hydrocarbon emissions can be reduced by increasing both the injection timing and the injector-opening pressure</td>
<td>Narayana and Ramesh (2006)</td>
</tr>
<tr>
<td>Engine performance of jatropha oil and its blends</td>
<td>Engine performance better for blends than neat vegetable oil. Specific fuel consumption reduced. Thermal efficiencies were acceptable for B50.</td>
<td>Pramanik (2003)</td>
</tr>
<tr>
<td>Performance of different composition of rubber seed oil blends in a 5.5 kW single cylinder direct injection compression-ignition engine.</td>
<td>Among four blends B20, B40, B60 and B80; B20 gave satisfactory thermal efficiency and specific fuel consumption. However, heavy carbon deposits were formed.</td>
<td>Ramadhas et al. (2005)</td>
</tr>
<tr>
<td>Evaluation of biodiesel behavior during auto-ignition process and its behavior in diesel fuel injection systems</td>
<td>Use of both neat and blended biodiesel altered fuel injection and ignition processes in engines. Biodiesel yields diesel soot that can be oxidized easily.</td>
<td>Szybist et al. (2007)</td>
</tr>
<tr>
<td>Use of exhaust gas recirculation to reduce engine emissions</td>
<td>Larger reduction in NOx emissions could be obtained but this was offset by higher particulate and unburned hydrocarbon emissions.</td>
<td>Ladammatos et al. (1998)</td>
</tr>
<tr>
<td>Effect of different B10 fuels (castor, jatropha and erica sativa)</td>
<td>B10 of tamarind gave least emissions in comparison to castor and jatropha B10 but engine performance (power and torque) was poor.</td>
<td>Chakrabarti et al. (2011)</td>
</tr>
<tr>
<td>Combustion of different biodiesel fuels and prediction of exhaust mixture composition with and without exhaust gas recirculation (EGR)</td>
<td>Biodiesel with high H to C molar ratio gave less CO2 and O2 but higher H2O in exhaust, than lower ratio fuel. At similar air-to-fuel ratio, biodiesel combustion gases had more H2O and CO2 compared to diesel. With EGR, CO2 and H2O emissions were higher while O2 was lower for biodiesel.</td>
<td>Chuepeng and Komintaranach (2009)</td>
</tr>
</tbody>
</table>
Table 6 – Summary of results obtained for different tests conducted with UDWO in the internal combustion engine.

<table>
<thead>
<tr>
<th>Type of UDWO biodiesel</th>
<th>Tests performed</th>
<th>Highlights of research</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>UDWO</td>
<td>Emission...</td>
<td>Lower HC, CO, PAN and PM for UDWO biodiesel in first engine compared to diesel. NOx higher for biodiesel. In second engine biodiesel gave much less smoke in comparison to diesel. At a biodiesel : diesel fuel ratio of 1:1, it was observed that 1001 of biodiesel was consumed for engine performance tests.</td>
<td>Mittelbach and Tritthart (1988)</td>
</tr>
<tr>
<td>UDWO</td>
<td>Emissions and...</td>
<td>Emissions of CO, SO2 and CO2 decreased when using biodiesel in comparison to diesel. Smoke opacity decreased significantly. However, NOx and O2 increased. In addition, 9% less brake power was observed for biodiesel run diesel engine in comparison to diesel run engine.</td>
<td>Gonzalez-Gomez et al. (2000)</td>
</tr>
<tr>
<td>UDWO</td>
<td>Emissions and...</td>
<td>Smoke opacity reduced by 7% for B15. For both idle and full load, biodiesel fuel consumption rate was slightly higher than diesel. For full load, fuel consumption increased by 4% when diesel was replaced by biodiesel in the engine. The same was true for fuel consumption per kWh for a lorry engine.</td>
<td>Leung (2001)</td>
</tr>
<tr>
<td>UDWO</td>
<td>Emissions and...</td>
<td>CO emissions increased with increasing acid value. Low engine loads gave low NOx but increased with high loads. PM decreased significantly at high loads. Smoke opacity also decreased. Same thermal efficiencies for all three UDWO biodiesel fuels.</td>
<td>Hamasaki et al. (2001)</td>
</tr>
<tr>
<td>UDWO</td>
<td>Emissions testing of diesel and B10</td>
<td>CO reduced by 1.5% and HC by 44% when B10 used in place of diesel. However, NOx increased by 16% at 2500 rpm engine speed.</td>
<td>Leung (2001)</td>
</tr>
<tr>
<td>Palm oil</td>
<td>Emissions and...</td>
<td>B50 gave least emissions of CO, UBHCs*, CO2, O2 and smoke. For all biodiesel blends tested, B7s and B100 gave least brake specific fuel consumption, maximum brake power and maximum thermal efficiency.</td>
<td>Al-Widyan et al. (2002)</td>
</tr>
<tr>
<td>Recycled and grease...</td>
<td>Emissions and...</td>
<td>Smoke opacity reduced by 83% for biodiesel in comparison to diesel. CO and HC emissions decreased for biodiesel and NOx increase was marginal. Maximum engine power decreased in a linear fashion with increase in biodiesel blends in fuel tested in engine. Power output was less for biodiesel.</td>
<td>Guo et al. (2002)</td>
</tr>
<tr>
<td>Olive oil</td>
<td>Combustion...</td>
<td>Combustion efficiency similar for biodiesel and diesel. Fewer emissions of 59% for CO, 8.6% for CO2, 37.5% for NO and 58% for SO2 when using biodiesel. NOx emissions increased by 81%. BSFC* increased for biodiesel fuel.</td>
<td>Dorado et al. (2003)</td>
</tr>
<tr>
<td>Palm oil</td>
<td>Combustion...</td>
<td>At low energy rate, biodiesel combustion efficiency was higher than petroleum diesel whereas at high energy rate, diesel fared better.</td>
<td>Tashtoush et al. (2003)</td>
</tr>
<tr>
<td>UDWO</td>
<td>Emissions and...</td>
<td>Decrease in emissions for CO (8.6%), HC (31%) and PM (63%). Emissions increased for CO2 (2.6%) and NOx (5%). Wheel power and force decreased by 2.1% and 3.5%, respectively. Acceleration period reduced by 8.8% for 60–100 km/h range. 2.43% less fuel consumed when biodiesel replaced diesel in engine.</td>
<td>Ulusoy and Tekin (2004)</td>
</tr>
<tr>
<td>UDWO</td>
<td>Emissions and...</td>
<td>Much lower emissions for B20 and B100 with latter fuel giving least smoke production. B20 gave best engine power output and least BSFC.</td>
<td>Cetinkaya and Karasmanoglu (2005)</td>
</tr>
<tr>
<td>Type of UDWO biodiesel</td>
<td>Tests performed</td>
<td>Highlights of research</td>
<td>Reference</td>
</tr>
<tr>
<td>------------------------</td>
<td>-----------------</td>
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<td>-----------</td>
</tr>
<tr>
<td>Hazelnut soapstock and sunflower oil methyl esters</td>
<td>Emissions and engine performance</td>
<td>CO emissions higher at low speeds and lower at high speeds. Higher NOx and CO2 emissions for biodiesel and very low SO2. B5 to B25 gave higher brake power and torque than B25-B100. Highest values obtained for B17.5, after which, higher blends showed declining engine performance.</td>
<td>Usta et al. (2005)</td>
</tr>
<tr>
<td>UDWO and blends with glycerol</td>
<td>Effective pressure and engine performance of a direct injection diesel engine</td>
<td>Effective pressures of both fuels almost similar to each other and to petroleum diesel. 25% engine power loss, less maximum engine torque and 11.5% higher specific fuel consumption were noted for biodiesel in comparison to diesel fuel.</td>
<td>Ozkan et al. (2005)</td>
</tr>
<tr>
<td>UDWO</td>
<td>Exhaust gas temperatures and engine performance</td>
<td>Biodiesel exhaust gas temperatures less than diesel at all engine speeds tested. Brake power and torque were 3-5% lower for biodiesel in comparison to diesel fuel whereas fuel consumptions were marginally different.</td>
<td>Çetinkaya et al. (2005)</td>
</tr>
<tr>
<td>UDWO</td>
<td>Engine performance of naturally aspirated, three cylinder, marine outboard diesel engine</td>
<td>7.1% power loss was obtained when using biodiesel in comparison to diesel fuel, which was in accordance to the differences in calorific values of both fuels. Also B20 gave 1.5% loss of rated power whereas B100 resulted in 8% loss.</td>
<td>Murillo et al. (2007)</td>
</tr>
<tr>
<td>UDWO</td>
<td>Trace formation from tail gas exhaust of diesel engine</td>
<td>Biodiesel gave lower CO and SO2 emissions whereas PM, CO2 and NOx were higher. For B0, B50, 880 and B100, C12H12 was dominant tail gas species while CO, H2O was dominant for B20. Diethyl phthalate and diphenyl sulfone present.</td>
<td>Lin et al. (2007)</td>
</tr>
<tr>
<td>Palm oil</td>
<td>Emissions and performance evaluation on a direct injection engine using fresh and waste oil</td>
<td>Combustion temperature and pressure higher for diesel than biodiesel. Net emissions of NOx, COx, etc. similar for all 3 fuels. UBHCs and SOx2- emissions lower for UDWO-ME. Engine performance similar for biodiesel and diesel at part loads. Brake thermal efficiency losses of 1-1.5% for biodiesel.</td>
<td>Sudhir et al. (2007)</td>
</tr>
<tr>
<td>UDWO</td>
<td>Performance and emissions of direct, common rail injection using B0, B30, B70 and B100 fuels</td>
<td>Similar auto-ignition behavior for both methyl and ethyl esters of UDWO (sharp reduction in HC, PM and smoke opacity). Similar NOx emissions of biodiesel to diesel. As biodiesel quantity in blends increased, BSFC also increased while engine efficiency remained relatively constant at different modes of operation.</td>
<td>Lapuerta et al. (2008)</td>
</tr>
<tr>
<td>UDWO</td>
<td>Heat release, pressure increase rate, peak pressure and ignition delay of engine using diesel and blends of diesel/biodiesel fuel</td>
<td>Biodiesel and its blends found to give lower ignition delay, higher peak pressure, lower pressure increase rate and lower heat release in comparison to diesel. Biodiesel’s break specific fuel consumption was slightly higher than that for diesel and break thermal efficiency was lower by 2.5% for biodiesel.</td>
<td>Rao et al. (2008)</td>
</tr>
<tr>
<td>UDWO</td>
<td>Exhaust emissions, engine performance and temperature of direct injection compression ignition engine</td>
<td>UDWO-ME showed 22.5% reduction in smoke intensity, 17% in CO, 6.5% in exhaust temperature, 8% in CO2 and 1.5% in NOx. Maximum torque of 220 Nm for diesel and 217 Nm for biodiesel at 2200rpm. At 4000 rpm, maximum power for biodiesel was 72 kW and for diesel it was 72.4 kW. At 1750 rpm, minimum BSFC was 230 g/kWh for diesel and 259 g/kWh for biodiesel.</td>
<td>Utlu and Koçak (2008)</td>
</tr>
<tr>
<td>UDWO</td>
<td>Exhaust emissions and performance using B0, B20 and B50</td>
<td>CO and HC lower for B20 (19%) and B50 (27%) in comparison to B0, whereas NOx higher. PM for B20 was 21% lower than B0. BSFC decreased with engine load increase using B0 showing least fuel consumption per unit energy output.</td>
<td>Meng et al. (2008)</td>
</tr>
<tr>
<td>Type of UDWO biodiesel</td>
<td>Tests performed</td>
<td>Highlights of research</td>
<td>Reference</td>
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<tr>
<td>------------------------</td>
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<td>-----------</td>
</tr>
<tr>
<td>UDWO</td>
<td>Emissions and engine performance of diesel engine using B0, B30, B70 and B100</td>
<td>Sharp decrease in PM and smoke emissions for biodiesel fuels and reduction in mean particle size. Also biodiesel gave higher fuel consumption and similar brake efficiencies to mineral diesel fuel in the diesel engine.</td>
<td>Lapuerta et al. (2008)</td>
</tr>
<tr>
<td>Palm oil</td>
<td>Emissions and engine performance</td>
<td>B100 and B50 gave 25% and 18% less HC and CO emissions in comparison to No. 2 diesel. B100 emitted higher NOx than diesel. BSFC of B100 increased by 13% whereas that of B50 increased by 5.6% at engine loads of 0, 25 kW, 50 kW and 75 kW. At 50 kW load, engine efficiencies dropped by 0.26% for B100.</td>
<td>Lertsathapornsuk et al. (2008)</td>
</tr>
<tr>
<td>UDWO</td>
<td>Exhaust emissions and engine performance</td>
<td>CO, NO and NOx emissions decreased with biodiesel but NOx increased slightly in comparison to diesel. Although results of power tests for both biodiesel and diesel fuel were almost the same, BSFC for biodiesel increased by almost 8%.</td>
<td>Reefat et al. (2008)</td>
</tr>
<tr>
<td>Recycled cooking fat and UDWO</td>
<td>Engine exhaust emissions</td>
<td>At high engine loads, biodiesel fuel reduced CO and NOx emissions. In Perkins engine, 2% difference in exhaust temperature noted for biodiesel and diesel fuels whereas in Nanni engine, biodiesel temperature was higher (almost 12%).</td>
<td>Roskilly et al. (2008)</td>
</tr>
<tr>
<td>UDWO</td>
<td>Exhaust emissions and performance of engine using biodiesel and blends and ANN modeling</td>
<td>Blends of biodiesel with diesel gave very good emission profile in comparison to diesel. Correlation coefficients of 0.929 and 0.999 were achieved using the ANN model for predicting CO and HC emissions, respectively. For engine torque and BSFC, R² were 0.9487 and 0.999, respectively. Better engine performance for blends of biodiesel in comparison to pure biodiesel.</td>
<td>Ghobadian et al. (2009)</td>
</tr>
<tr>
<td>Palm oil</td>
<td>Exhaust emissions and engine performance of diesel engine and its prediction using neural network mathematical models</td>
<td>CO, HC and smoke opacity decreased with increasing biodiesel in blends with diesel whereas NOx increased. Models predicted results accurately. BSFC increased with biodiesel while brake thermal efficiencies and brake torque increased for the same fuel (neural network predicted the same results).</td>
<td>Canakci et al. (2009)</td>
</tr>
<tr>
<td>Cottonseed, rapeseed, soya bean and palm oil</td>
<td>Emissions profile from Cummins ISBe6 Euro III compression ignition engine</td>
<td>UDWO Biodiesel reduced PM, dry soot and non soot fraction from exhaust gases in a significant manner than other biodiesel fuels produced from fresh oil. However, NOx and HC emissions were relatively higher for UDWO biodiesel.</td>
<td>Wu et al. (2009)</td>
</tr>
<tr>
<td>Palm oil</td>
<td>Engine exhaust emissions of indirect injection engine running on full load and variable speed condition using biodiesel blends</td>
<td>Reductions of 57% in CO, 40% in HC and 23% in smoke opacity for biodiesel in comparison to diesel fuel because of increase in fuel line pressure and decrease in ignition delay and air-fuel equivalence ratio in the biodiesel fuelled engine. NOx and CO2 were found to increase.</td>
<td>Ozseen and Canakci (2010)</td>
</tr>
<tr>
<td>UDWO</td>
<td>Engine performance and emissions evaluation of a direct injection engine using blends of biodiesel</td>
<td>B50 gave 6.5% less brake thermal efficiency and almost 7% higher BSFC in comparison to diesel. CO and PM reduced within the ranges of 21%–45% and 23–47% for biodiesel blends. SO2 emissions were found to be significantly lower by about 50–100% due to minimal sulfur content of B100 fuel.</td>
<td>Hirkude and Padalkar (2011)</td>
</tr>
<tr>
<td>UDWO</td>
<td>Engine emissions and performance analysis of B0, B5, B10, B20 and B30 in direct injection, Cummins B5.9–160, engine</td>
<td>Biodiesel blends decreased PAHs by 8–38%, PM by 5–8%, HC by 11–36% and CO by 3–13% in comparison to the use of ultra low sulfur diesel fuel on its own. BSFC for biodiesel was higher but volumetric consumption of both fuels was quite similar mainly because biodiesel has lower calorific value and higher density than diesel fuel, respectively.</td>
<td>Lin et al. (2011b)</td>
</tr>
</tbody>
</table>
Generally, literature reports that biodiesel properties are comparable to petro-diesel. Blending the fuel characteristically been associated with reduced ignition delay, increased ignition temperature and raised ignition pressure and peak heat release (Basha et al., 2009; Chakrabarti et al., 2010, 2011). Other related findings are given in Table 5.

6. Biodiesel from UDWO in engines: performance analysis

Enweremadu and Rutto (2010) showed in their review that biodiesel produced from UDWO had similar fuel properties to biodiesel from refined oils or fats. They also concluded that the performance of biodiesel from both UDWO as well as refined oil was closely related (Enweremadu and Rutto, 2010).

A similar review that covered the effect of biodiesel in diesel engines confirmed the same (Xue et al., 2011). The same was also deduced by Canakci and Van Gerpen (2003) by evaluating engine performance (in terms of brake specific fuel consumption and brake thermal efficiency) and emissions (especially particulate matter) using biodiesel from yellow grease oil in comparison to biodiesel from refined soya bean oil. Emissions analysis of a direct injection CI engine using biodiesel from sunflower oil and UDWO gave almost identical results in terms of a significant decline in smoke opacity (Armas et al., 2006). A very recent investigation comparing the engine performance and emissions of methyl esters of fresh canola oil and waste palm oil showed that both fuels gave almost identical results (Ozaezen and Canakci, 2011). Table 6 summarizes results of combustion characteristics, engine emissions and engine performance of numerous UDWO biodiesel fuels in the CI engine.

In general, it appears that biodiesel produced from both fresh oil and UDWO produce similar results in the CI engine. This gives an added advantage to UDWO methyl/ethyl esters due to economic considerations as mentioned in earlier sections. This is so provided UDWO is generated in large quantities in the particular region of study. For example, waste grease in Pakistan is used for production of soap and hence is not always available for biodiesel production (Khan and Dessouky, 2009). Hence the benefits accrued from the use of UDWO as raw material for biodiesel may be limited in some undeveloped countries. However, an overall scenario throughout the globe seems to indicate quite a large production of UDWO and hence its conversion to biodiesel can definitely benefit many economies if harnessed at a large scale in the near future.

7. Benefits of UDWO utilization

Currently, most of the sourced UDWO is either disposed or marketed for use as additives in animal feed despite the ban on its utilization in the feed formulation. Thus, producing biodiesel from UDWO can be an effective and economical approach to managing this energy source as it provides a dual benefit of generating fuel and also protecting the environment. For the latter case, reducing or eliminating the use of waste oil domestically negates the worrisome scenario of returning the harmful constituents of the UDWO back to the food chain by means of animal feed additives (Cvengros and Cvengros, 2004).

One of the main merits of utilizing UDWO as a feedstock for biodiesel is not only limited to fuel diversification but also in mitigating the environmental pollution, especially its global
warming consequences as the waste is no longer dumped into the sewage network (Tsai, 2010). The biodiesel from this feedstock is environmentally accepted due to lower emissions of harmful air pollutants as compared to petro-diesel fuel (Ozesen et al., 2009). As a readily available, cost effective biodiesel feedstock, the UDWO can potentially replace diesel fuel in the short term and on the long run reduce the dependency on petroleum based fuel (Issariyakul et al., 2007). The fact that UDWO is abundant in large quantities globally, they can be strategically used in biodiesel production thus positively affecting trade balance by eliminating or reducing the need for fossil fuel imports. Moreover, the generation of biodiesel from UDWO as a form of oxygenated fuel is found to be technically feasible; it thus serves as a medium for contributing significantly to sourcing the target fuel from cheaper feedstock sources. Despite the ban imposed on the use of UDWO as animal feedstock, its potential application in biodiesel production further serves to discourage its use for the former, thereby effectively achieving its removal from the system. This does not affect the food chain as UDWOs are not part of the food chain in the first place (Araujo et al., 2010).

As established in Section 3, the amount of UDWO generated is significant on a continuous basis. Its utilization for fuel generation serves as a window for job creation as the process is relatively labor-intensive; thus in developing and the rural economies it would translate to a positive impact.

8. Conclusions

Environmental concerns, production cost, associated hazards and sustainability issues have plagued fossil fuel utilization. However, biodiesel usage is less affected by most of these factors as it is renewable, environmentally friendly and can be produced from a variety of feedstocks in respective regions. Thus, the urgency to replace 20% and 30% of petro-diesel with biofuels in the US and EU by 2020 and 2030, respectively, can be justified. However, the interest of attaining the annual targeted production rate of 227 billion liters calls for increased production of biodiesel. Despite the efforts being made by the EU, it is not self-sufficient to meet its biodiesel target. The fact that current biodiesel requirements cannot be fully met from traditional feedstock, exploring other relatively cheaper feedstock sources may significantly contribute towards augmenting future demand and this issue has become of paramount importance. Thus the search for more alternative feedstock that minimizes the production cost, the feedstock represents 70-90% of total production cost, is a continual one.

An interesting feedstock for biodiesel production is used domestic waste oil (UDWO), wastes hitherto meant for disposal. These would go a long way in minimizing importation of biomass in several countries. This goes in addition to the fact that UDWO results in significant environmental loading if it is disposed in the normal sewage network. Thus, their conversion offers the merits of greenhouse gas emission (GHG) reduction, potentials for enhancing fuel diversification and a qualitatively comparable energy output to fossil diesel fuels. Although, certain drawbacks such as the high free fatty acid limit its transesterification reaction, various approaches have sufficiently addressed the problem and an optimum yield of 99.3% has been recorded.

Among the various feedstocks considered for UDWO methyl esters, the most notable ones that subsequently underwent engine testing included olive oil, palm oil, coconut oil, sunflower oil, canola oil, trap grease oil and waste anchovy oil. In general, biodiesel from UDWO was observed to decrease engine emissions of priority pollutants by significant amounts in comparison to the implementation of petro-diesel fuel. For instance, carbon monoxide, unburned hydrocarbons, particulate matter, sulfur dioxide, polycyclic aromatic hydrocarbons and smoke were found to reduce within ranges of 15-60%, 21-45%, 23-63%, 50-100%, 8-40% and 16-83%, respectively. However, emissions of NOx and CO2 were found to increase within the ranges of 5-81% and 3%, respectively. Similarly, engine exhaust temperature was found to increase with biodiesel by approximately 10%. Differences in the range were due to factors such as the source of oil for producing UDWO, firing procedure and firing time. However, most authors that compared the emission performance of engines for both fresh vegetable oil and UDWO methyl esters commented that the results were almost the same or marginally different. In addition, biodiesel blended with petroleum diesel was more polluting than pure biodiesel tested on its own in the CI engine (this factor also played a significant part in giving wide pollutant ranges mentioned above).

The engine performance of UDWO biodiesel was similar to that for fresh vegetable oil methyl esters. However, the engine performance of biodiesel was slightly lower than petro-diesel due to having a lower calorific value. Depending on the source of the UDWO and its respective calorific value, engine parameters such as brake power, torque, brake specific fuel consumption and brake thermal efficiency were found to decrease within ranges of 1-25%, 3-5%, 7% and 1-7%, respectively, for biodiesel in comparison to diesel fuel in the CI engine.

For proper utilization of UDWO a ban on its utilization for animal feed supplements is not sufficient. It is recommended that governments should support the initiative with incentives. By providing adequate incentives, 70% of the used cooking oil could be recovered from restaurants and other sources thus resulting in waste to energy for various economies throughout the world. A holistic look at the use of UDWO in generating biodiesel transcends beyond addressing waste disposal management through healthier approach but also serves as a window for poverty reduction and meeting the US and EU targets. As further research, it may be useful to evaluate methods of improving combustion efficiency as well as the calorific value of UDWO in order to match or excel the combustion characteristics of its fossil counterpart in the CI engine.

References


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