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# Transesterification Reaction and Comparative Study of the Fuel Properties of Biodiesels Produced from Vegetable Oils: A Review

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## Abstract

Biomass, of animal or plant origin, has been a highly sought-after energy resource for centuries. Like bioethanol, biodiesel is a fuel produced from biomass and mainly vegetable oils or animal fats. The production of these fuels helps to reduce greenhouse gases and stimulate the local economy. This bibliographic synthesis constitutes a scientific contribution to the production of quality biodiesel, produced locally and more profitable. To do this, we consulted and synthesized the recent information available. Comparisons were also made. At the end of this research, it appears that biodiesel is generally produced by transesterification, interesterification, microemulsification or pyrolysis in order to approximate its characteristics to those of petrodiesel. Transesterification is the most widely used because of its low cost, simplicity, best yields and the quality of the biodiesel obtained. To optimize biodiesel production in this way, operating parameters must be controlled. These are: the type and concentrations of alcohol and catalyst used, the temperature and reaction time, the water content of the alcohol and vegetable oil, the free fatty acid content of the oil and the agitation rate of the reaction medium. The use of distilled water for purification, thin layer chromatography for the quantification of ethyl esters and a probable substitution of the base by a solution of ash from palm nut residues or cotton seeds, would be an asset to limit economic burdens and encourage local production.

## Keywords

Biomass, Biodiesel, Transesterification, Operating Parameters

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## 1. Introduction

The industrial revolution has increased the use of fossil fuels [1]. Despite various initiatives towards other forms of non-fossil energy, they remain to date the world's main energy sources. With the ever-increasing evolution of the planet's population and the consequent increase in energy needs, fossil energies will experience a considerable fall in the imminent future (after 2025) [2]. In addition to their high cost, they emit greenhouse gas emissions (carbon dioxide, carbon monoxide, total hydrocarbons, nitrogen

oxides, sulphur dioxide, etc.) and regional insecurities [3, 4, 5]. Apart from the above, the first oil shock of 1973 caused by the Arab-Israeli conflict boosted developed countries' investment in other energy resources, particularly renewable energies, to reduce fossil energy dependence [2]. Biofuels are part of this promising energy category for the environment. Compared to fossil fuels, biofuels present little or no risk to the environment due to their total ultimate biodegradability and low toxicity to animal species and micro-organisms [6]. However, biodiesels produce oxygenated hydrocarbons at low temperatures and cause engines to brake thermally.

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Indeed, in the combustion chambers, vegetable oils undergo physical, chemical changes with the formation of undesirable materials consisting among others of polymerized fatty acids (gums), certain triglycerides and a large quantity of carbon. The latter increase molecular weight and reduce oil volatility [7] which requires pre-treatment of the oils before use as engine fuel. Despite these controversies, biofuels remain and remain a highly coveted alternative source of fossil fuels [8-10]. According to Beulin [11], they emit less carbon dioxide than gasoline and diesel. They limit energy dependence on producing countries and provide a new outlet for local farmers [12-14].

Most vegetable oils have a higher viscosity than diesel at room temperature with a long ignition delay. Even when purified and refined, vegetable oils exhibit high heat of evaporation and incomplete distillation due to their fatty acid composition [15]. A transformation of these oils is essential for them to acquire the property of fuel for diesel engines. In general, biodiesel is produced by transesterification, with or without catalyst, enzymatic interesterification, microemulsification or pyrolysis. Transesterification (with acid, basic or enzymatic, homogeneous or heterogeneous catalysts) is the most widely used reaction [16-18]. It is a complex operation because of its intrinsic characteristics: two-phase medium, several consecutive balanced reactions with several reaction intermediaries, competitive reactions (soap formation), etc. [18]. Vegetable oil methyl esters (VOMEs) are essentially produced by a catalyzed transesterification reaction between the triglycerides contained in the oils and methanol. Methanol is synthesized by natural gas from fossil resources. To obtain 100% biodiesel of renewable origin, vegetable oil ethyl esters (VOEEs) are preferred. Indeed, VOEEs can be obtained by using ethanol and more specifically bioethanol from the fermentation of sugars contained in plants [18, 19]. This bibliography synthesis aims at the appropriation of the transesterification reaction and the economically profitable reaction conditions for a biodiesel production. It is a first step towards the development of local non-conventional oilseed plant resources.

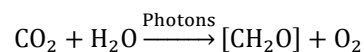
## 2. General information on Biofuels

### 2.1. Biomass

According to European Directives 2001/77/EC of 27 September 2001 and 2009/28/EC of 23 April 2009, biomass is defined as "the biodegradable fraction of products, waste and residues from agriculture (including plant and animal substances), forestry, aquaculture and related industries, as

well as the biodegradable fraction of industrial and municipal waste" of biological origin [22, 23].

Plant biomass results from photosynthetic reactions in which the light energy released by the sun allows carbon dioxide to be fixed on water to produce organic matter according to the equation below [24].



### 2.2. Importance of Biomass for Renewable Energy Production

Energy sources are broadly classified into two groups: fossil fuels and renewable energies [25, 26]. Fossil energy sources include coal, oil, natural gas, liquefied gases and fossil materials, while renewable energy sources include biomass, hydro, geothermal, solar and wind kirtaz [27, 28].

The global transport sector is currently almost completely dependent on petroleum-based fuels. In addition, the transport sector accounts for over 70% of global carbon monoxide (CO) emissions and 19% of global carbon dioxide (CO<sub>2</sub>) emissions [4]. CO<sub>2</sub> emissions from one gallon of gasoline are approximately 8 kg [5]. Worldwide, there were approximately 806 million cars and trucks on the road in 2007 [20]. This number is projected to increase to 1.3 billion by 2030 and to over 2 billion vehicles by 2050 [21]. This growth will affect ecosystem stability and global climate as well as global oil reserves. The exorbitant increase in oil prices, the depletion of fossil fuels, greenhouse gas emissions and regional insecurities (geopolitical and geostrategic) open the way to other energy sources [3]. Today, nuclear power, for safety reasons (Chernobyl and Fukushima accidents), represents only 3% of the world's energy supply. For solar and wind energy, the most common criticism is their intermittent nature and storage difficulties. That is why their contribution is still small. Based on these remarks, biomass, which currently represents 18% of the world's energy supply, could in a few decades constitute the main alternative to fossil fuels [10]. In the field of transport, the best way to recover energy from biomass is to convert it into biofuels.

### 2.3. Biofuel Production Chains

In general, bioethanol or biodiesel production chains are traditionally divided into four generations, depending on the raw materials and technologies used [19]. Biodiesel does not require a particular quality of the original raw material. However, in order to reduce the overall cost of biodiesel production, it should be inexpensive and biodiesel production should be local if possible. There are several generations of biofuels:

- 1 The first generation of fuels uses conventional technologies to transform only the food portion of crops

(i.e. sugars and starch) into bioethanol and the oil portion of plants or animal fat (i.e. oil in its pure state or incorporated into diesel) to produce biodiesel [19].

- The second generation aims at the entire valorisation of plants, i.e. lignocellulosic biomass into bioethanol using advanced technologies. Because of its high octane number, low cetane number and high heat of vaporization, bioethanol blend is capable of replacing gasoline [29].
- The third generation exploits the potential of algae and microalgae for biofuel production with very high processing technologies. Biodiesel, bioethanol, biogas, biobutanol, biomethane are formed by the biochemical process and synthesis gas by the thermochemical process [29]. Microalgae are recognized as a potential source of oil with a very rapid photosynthesis capacity [30].
- The fourth generation follows the same processing steps as the third generation with the difference that the fourth generation envisages genetic modification of microalgae for high carbon dioxide sequestration capacity and high oil yield [29]. For Demirbas [31], the fourth generation also integrates technology pathways such as pyrolysis, gasification, solar-fuel and genetic transformation of organisms to secrete hydrocarbons.

The reduction of greenhouse gases is more pronounced with the second, third and fourth generation of biofuels. Economically, the first generation is more profitable.

However, this profitability varies according to the conversion processes used [29].

#### 2.4. Biodiesel

Biodiesel is any liquid fuel derived from organic acids derived from vegetable oils or animal fats that can be used in diesel engines. They can be used alone or mixed with petrodiesel in different proportions. Biodiesel consists of alkyl esters and is generally made by chemical reaction between lipids and alcohol. During its synthesis, a considerable amount of glycerol is produced [32].

### 3. Processes for Converting Vegetable Oils to Biodiesel

Two ways of converting biomass into energy are commonly distinguished: thermochemical pathways, also called dry pathways, which transform biomass under the action of heat and biochemical pathways, also called wet pathways, which use biological conversion processes [9]. Biodiesel is a biofuel produced from vegetable oils or animal fats. In general, it is produced by enzymatic transesterification, microemulsification, pyrolysis, dilution or transesterification

with or without catalyst. The latter method is the most commonly used reaction in the presence of homogeneous or heterogeneous acid, basic or enzymatic catalysts [17, 33]. Indeed, it is the simplest with better yields and good quality biodiesel obtained [34].

## 4. Transesterification Reaction

Transesterification is a transformation in which one alcohol is displaced by another alcohol in a triglyceride. Depending on the alcohol used (methanol or ethanol), we obtain biodiesels consisting mainly of methyl esters or ethyl esters (Figure 1). In addition to mono and diglycerides, there are also unprocessed triglycerides. The main esters contained in biodiesel are oleic, linoleic, linolenic, erucic, stearic, palmitic and caprylic. They are obtained in varying proportions, depending on the types of alcohol and oil used during transesterification [17].

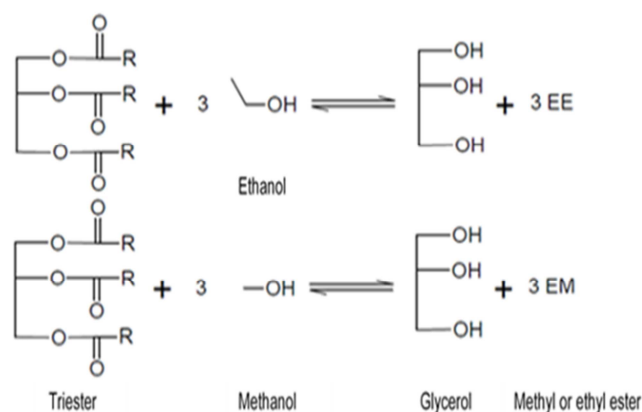


Figure 1. Transesterification reactions.

#### 4.1. Conventional Transesterification Reaction Process

In a reactor, a mixture of oil, alcohol and catalyst is made. After transesterification, the reaction mixture is transferred to a decanter and the glycerol-rich phase forming a lower layer is removed. At the end of the reaction, the reaction mixture contains different compounds (formed esters, free fatty acids, glycerides, glycerol, alcohol, catalyst residues, soaps, water) in different proportions and divided into the two phases. This was followed by purification of the biodiesel to remove catalyst residues in the glycerol-rich phase with mineral acids (H<sub>3</sub>PO<sub>4</sub>, HCl) followed by decantation. A distillation at reduced pressure allows the alcohol excess to be recovered and several stages of washing the ester phase with hot distilled water remove the remaining impurities. A desiccant (Na<sub>2</sub>SO<sub>4</sub> or MgSO<sub>4</sub>) is used at the end to remove traces of water in the purified biodiesel. The overall scheme of the process is as follows:

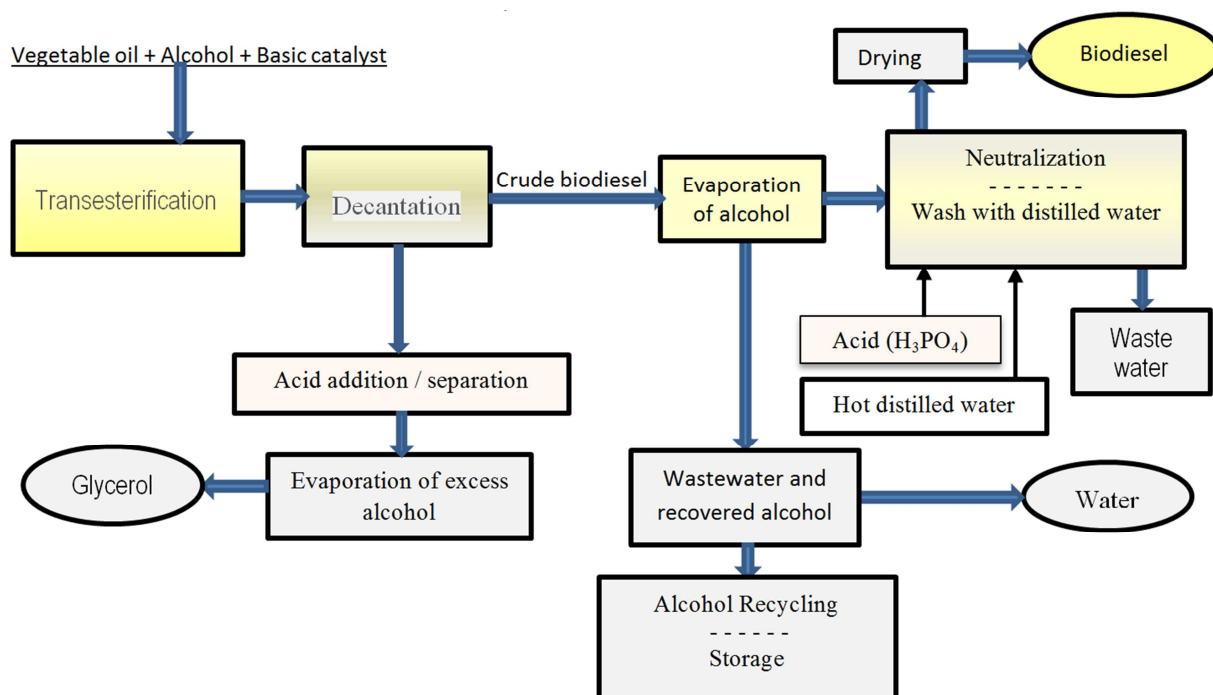


Figure 2. Conventional biodiesel production process by basic catalysis [34].

## 4.2. Kinetic Factors of the Reaction

These are factors whose knowledge and mastery make it possible to optimize the conversion of vegetable oils into biodiesel.

### 4.2.1. Catalyst Concentration

Concentration is the most important kinetic factor compared to temperature and the alcohol / oil molar ratio [35]. A distinction is made between homogeneous and heterogeneous catalysis in the transesterification reaction.

#### 1 Homogeneous catalysis

This catalysis involves catalysts that are in the same (liquid) phase as the reactants during the reaction. These catalysts can be acidic, basic or enzymatic. The first two, the least expensive, produce products that are difficult to separate [36].

The most commonly used basic catalysts are sodium hydroxide, sodium methoxide (or ethoxide), potassium hydroxide and potassium methoxide (or ethoxide). Sodium hydroxide and potassium hydroxide are the most widely used because of their low cost compared to sodium or potassium methoxide (or ethoxide). The latter avoid the formation of water which promotes the saponification reaction. Under the same conditions with similar results, transesterification with methanol requires less sodium methoxide than sodium hydroxide [33, 37, 38]. With these catalysts, the reaction is rapid and takes place under moderate conditions. However, these basic catalysts lead to soap formation when the free

fatty acid content in vegetable oils is high, making separation difficult [35].

With the most commonly used acid catalysts such as hydrochloric acid, sulphuric acid, phosphoric acid but also sulphonic acids, the reaction occurs over a relatively longer time with or without water formation [36, 39]. Inedible vegetable oils or frying oils are often richer in free fatty acids than edible vegetable oils. Under these conditions, acid catalysts are more indicated with better results. Esterification of free fatty acids is often recommended before basic ethanolysis [36, 37].

For this reason, 1% sulphuric acid was initially used by Berchmans and Hirata [40] to reduce the acidity of *Jatropha curcas* vegetable oil from 15% to less than 1%. This esterification reaction occurred with a methanol/oil ratio of 0.60 (m/m) for 1 h at 50°C followed by 2 h cooling. The product obtained after removal of the higher fraction consisting of methanol - water, underwent transesterification at 65 °C for 2 hours with methanol/oil ratios of 0.24 (m/m) and NaOH/oil ratios of 1.4% (m/m) for a yield of 90%. Other work confirms the reduction of the acidity of *Jatropha curcas* vegetable oil from 14% to less than 1% in the first stage with 1.43% v/v H<sub>2</sub>SO<sub>4</sub>, a methanol/oil ratio of 0.28 v/v at 60°C for 88 min. A 99% yield is obtained following the lower phase transesterification reaction that lasted 24 min at 60°C with methanol/pretreated oil ratios of 0.16 v/v and KOH/pretreated oil ratios of (0.35 + new acidity) % m/v [41].

#### 2 Heterogeneous catalysis



It combines recyclable and reusable catalysts several times with an easier purification of the final product. Over time, however, there has been a decrease in the activity of these catalysts in transesterification [38]. These catalysts occur in various physical states (solid, immiscible liquid and gas) than reactants [37]. Common catalysts include vanadium phosphate, various metal oxides (active calcium, magnesium, zinc, aluminium, barium, etc.), solid resins. Calcium oxide (CaO) is most commonly used in the transesterification reaction with a yield of over 98% methyl esters in one step followed by magnesium oxide. Compared to homogeneous catalysts, the conversion rate with heterogeneous catalysts remains lower (80-90% after 1 h of reaction) [17, 37].

The use of lipases is limited because of their high cost, reducing their reactivity by phospholipids contained in vegetable oils. They are also inhibited by methanol and ethanol for future reuse. However, lipases allow transesterification of vegetable oils with high free fatty acid contents of up to 75% by mass with a relatively longer time than in basic homogeneous catalysis. The inhibitory effect of alcohols can also be avoided by replacing them with methyl or ethyl acetate [17]. Among the most commonly used enzymes are Novozyme 435, Lipozyme RM IM and Lipozyme TL IM, *Thermomyceslanuginosus* Tsikl. and *Rhizomucormiehei*.

#### 4.2.2. Water Content of Vegetable Oil and Alcohol

For very high levels of free fatty acids, the oil may undergo a first esterification stage before the actual transesterification. This first reaction being reversible, the excess of alcohol and/or the elimination of water contribute to shift the balance in the direction of the formation of the products. According to Lu et al [42], Berchmansand Hirata [40], the higher the water content present during the reaction, the lower or zero the reaction yield.

#### 4.2.3. Rate of Agitation of the Reaction Medium

The stirring speed is a very important parameter in the kinetics of the transesterification reaction, especially high at the beginning of the reaction (first 10 minutes). Indeed, ethanol and methanol are not miscible with triglycerides at room temperature or even heated [17]. Agitation of the oil-alcohol mixture at the beginning of the reaction is necessary to improve mass transfer. At the end of the reaction, agitation is interrupted to facilitate separation of an ester-rich phase and a glycerol-rich phase [43-45]. Agitation increases mass transfer by dispersing fine alcohol droplets in the triglyceride phase and thus improves contact between the two reactants [46]. The reaction takes place at the interface of the alcohol droplets dispersed in the oil. As esters form, the solubility of

alcohol in the triglyceride phase increases: esters act as a common solvent for alcohol and triglycerides [47]. Because of the immiscibility of the reaction mixture at the beginning of the reaction and the considerable presence of the mono- and diglycerides formed afterwards, vigorous agitation can cause the formation of emulsions that reduce the reaction yield [47-50]. For example, the recommended agitation rates for reaction mixing are generally 600 to 1000 rpm for 0.5 to 2.0 L reactors and 150 to 400 rpm for reactors less than 0.3 L [17]. It should also be noted that mechanical agitation is more effective in some cases than magnetic agitation [8, 43, 51].

#### 4.2.4. Temperature and Reaction Time

There is a correlation between time and reaction temperature. Transesterification reactions taking place at room temperature require a sufficiently long time. These reactions are mostly exothermic with a temperature variation of about 5°C at the end of the reaction. To reduce the reaction time, heating is necessary. The transesterification reaction occurs at temperatures near the lower end of the alcohol range [17, 38]. Marchetti et al [36] reported that the reaction temperature varies between 25 and 120°C depending on the catalyst. The same work mentioned that with basic, acid and enzymatic catalysts, methanolysis temperatures vary respectively between 60°C and 70°C; 55°C and 80°C then 30°C and 40°C. It is important to note that temperature has no effect on the thermodynamic balance of the reaction. Indeed, whatever the temperature, the reaction medium has the same composition at the end of the reaction (for an infinite time) [18].

#### 4.3. Purification of Biodiesel

The biodiesel resulting from the transesterification reaction and mainly consisting of methyl or ethyl esters of fatty acids, contains impurities such as unreacted methanol or ethanol, soaps, etc., which are not subject to the reaction. It therefore requires some form of purification before its use in diesel engines. All impurities being polar, water is a suitable solvent for dissolving them. To do this, a maximum amount of 20% by weight of distilled water relative to the amount of transesterified oil is poured slowly over the product after neutralization with acetic acid [17, 52]. This step requires great care with less agitation to avoid the formation of emulsions that negatively affect the yield of synthesis. The mixture of water and biodiesel is left for 16 hours or even 24 hours in a separating funnel to separate the aqueous phase containing impurities from the biodiesel phase. After 1 hour of heating at 100°C, the biodiesel is rid of the remaining water molecules [53]. Lu et al. [42] also highlight the beneficial effect of water at the end of transesterification for the precipitation and removal of phospholipids contained in vegetable oils.

#### 4.4. Optimal Conditions For transesterification of Some Vegetable Oils

Based on the results in Table 1, most ethanolic or methanolic transesterification reactions take place between 30 and 120 min depending on the alcohol and the type of

catalyst (KOH or NaOH) used. With a higher acidity of vegetable oils, the reaction takes place in an acid medium with a sufficiently long time interval and a higher alcohol: vegetable oil ratio. This acidity is also proportional to the ratio of alcohol to vegetable oil when either of the above catalysts is used.

**Table 1.** Optimal conditions for transesterification of some vegetable oils in one step.

Species	alcohol, % (m/m)	Molar ratio, alcohol: oil	Ac. %	Cat. type: con. % (m/m)	T, °C	Time, min	R, % (m/m)	References
<i>Adansonia digitata</i>	MeOH	30:1	2	NaOH: 1.4	60	60	96	[54]
	EtOH	12:1	0.14	KOH: 1	50	90	96	[55]
<i>Cyperus esculentus</i>	MeOH	1:4.5a	ND	KOH: 0.9b	55	60	67	[52]
	MeOH	1:6a	8.97	KOH: 0.65	60	60	82	[56]
<i>Hura crepitans</i>	MeOH	6:1	2.38	KOH: 1	38	30	92	[57]
	EtOH	6:1	ND	KOH: 1.5	65	107	94	[58]
<i>Jatropha curcas</i>	MeOH	5:1	ND	KOH: 0.55b	60	30	92.70	[59]
	MeOH	1:5a	ND	NaOH: 1	50	120	89	[60]
	EtOH, 95	30:1	ND	H <sub>2</sub> SO <sub>4</sub> : 1	78	1440	30	[61]

T°C: Reaction temperature in degrees Celsius; reaction mass efficiency (R, %); alcohol/oil volume ratio (v/v), bg KOH/100mL-oil; cat: catalyst; Ac: acidity; ND: Not Detected

## 5. Physico-chemical Properties and Fatty Acid Composition of Some Vegetable Oils

### 5.1. Physico-chemical Properties of Some Vegetable Oils

Table 2 shows vegetable oil contents between 35-50%, 15-40%, 34-70% and 49-58% respectively for *Adansoniadigitata*,

*Cyperusesculentus*, *Huracrepitans* and *Jatrophacurcas*. The highest values are obtained with the lowest water contents of oil seeds and tubers. Apart from the vegetable oil of *Jatrophacurcas* whose iodine and saponification indices of the various authors are very close, all the other species give values very dependent on their sources. These two sizes are for the most part greater than 100 and testify to the unsaturation of vegetable oils and their use in soap making.

**Table 2.** Physico-chemical properties of some vegetable oils.

Species	Oc (%)	Wc (%)	V (mm <sup>2</sup> /s)	D	AV (mg KOH/g)	PV (méq O <sub>2</sub> /kg)	IV (gI <sub>2</sub> /100g)	SV (mg KOH/g)	References
<i>Adansonia digitata</i>	35.50-39.60	ND	3.49	0.880	0.047	ND	124.87	210.38	[62]
	35.90	8	ND	ND	0.421	1.40	98.07	122.60	[63]
	49	1.67	18.69	0.894	0.28	ND	114.20	96.80	[55]
	28	0.06	23.91	0.896	1.77	8.75	72.89	178.54	[64]a
	37.49	0.05	24.43	0.898	1.56	7.95	79.73	178.09	[64]b
<i>Cyperus esculentus</i>	15.91	5.32	0.98	0.910	8.97	8.33	143.37	161.54	[56]
	ND	ND	12.70	0.896	1.69	ND	88.46	170.34	[65]
	30	3.75	ND	ND	1.59	0.30	113	209	[66]
	69.32	0.40	6.44	0.920	4.76	15	127.53	193.20	[57]
	37.75	ND	ND	ND	4.41	ND	120.10	210.10	[67]
<i>Hura crepitans</i>	34.80	1.90	ND	0.896	52.08	ND	109	149.12	[68]
	53.61	7.28	ND	ND	27.09	3.83	177.66	245.98	[69]
	38.20	ND	ND	ND	1.64	2.14	122.08	210.38	[70]
	49	ND	17.10	0.919	2.985	0.30	100	199	[71]
<i>Jatropha curcas</i>	47.25	5.54	17.10	0.919	3.50	ND	105.20	198.85	[72]
	57.40	4.40	37	ND	1.20 – 2.50	ND	106.60	190.10	[73]
	ND	0.08	ND	ND	25.36	ND	ND	ND-	[61]

Oc: Oil content; Wc: Water content; V: Viscosity; D: Density; IV: Iodine value; AV: Acid value; PV: Peroxide value; SV: Saponification value; ND: Not detected; a: yellow *Cyperusesculentus*; b: black *Cyperusesculentus*.

## 5.2. Acid Composition of Some Vegetable Oils

The fatty acid composition of the various vegetable oils reveals the predominance of unsaturated fatty acids. For a given oilseed species, this composition varies according to the source consulted. Apart from this variability, the predominance of oleic acid is frequently noted, especially in vegetable oils of *Cyperus esculentus* where its content varies between 60 and 70%. The vegetable oils of *Adansonia digitata*, *Huracrepitans* and *Jatropha curcas* sometimes contain similar proportions of oleic acid and linoleic acid (Table 3). According to some authors, a high linoleic acid content can be recorded. In fact, Modiba et al [54] evaluated 27.47% linoleic acid followed by

22.14% oleic acid in *Adansoniadigitata* vegetable oil. This content can exceed 70% oleic acid found in vegetable oils of *Cyperus esculentus*. This is the case of 81.31% linoleic acid quantified in *Huracrepitans* vegetable oil by Ezech et al [70]. Of all the sources consulted on *Adansonia digitata* vegetable oil, only Eteshola and Oraedu [74] noted a predominance of myristic acid (saturated fatty acid). Differences in fatty acid composition may be influenced on the one hand by methods of extraction, packaging, characterization of vegetable oils and on the other hand by the environment and genotype [75]. It should be noted that C17:0, C22:0 and C24:0 fatty acids are very rare in the oils investigated.

Table 3. Fatty acid composition of some vegetable oils.

Species	<i>Adansonia digitata</i>				<i>Cyperus esculentus</i>				<i>Hura crepitans</i>				<i>Jatropha curcas</i>					
Saturated fatty acids (%)	C14:0	ND	0.3	38.4	0.2	0.13	ND	1.7	0.1	0.8	0.18	ND	ND	ND	0.1	0.1	0.04	0.06
	C16:0	20.96	26.7	19.7	24.2	16.5	15.94	15.4	13.1	14.5	21.67	12.2	4.4	16.92	14.2	13.6	13.98	15.56
	C17:0	ND	0.2	ND	ND	ND	ND	ND	ND	ND	0.31	ND	ND	ND	0.1	ND	ND	0.08
	C18:0	20.29	5.9	3.2	4.6	6.87	9.84	5.3	2.8	3.4	9.66	5.1	4.59	1.76	7	7.4	6.45	7.34
	C20:0	0.29	0.9	ND	1.3	ND	1.55	6.1	0.7	0.2	2.48	0.2	ND	ND	0.2	0.3	0.17	0.19
	C22:0	ND	0.6	ND	0.7	ND	ND	ND	0.2	ND	0.31	0.3	ND	ND	ND	ND	0.03	ND
	C24:0	ND	ND	ND	0.2	ND	ND	ND	0.8	ND	0.49	ND	ND	ND	ND	ND	ND	ND
Totals	41.54	34.6	61.3	31.2	23.5	27.33	28.5	17.7	18.9	35.1	17.8	8.99	18.68	21.6	21.4	20.67	23.23	
Unsaturated fatty acids (%)	C16:1	ND	0.2	ND	ND	0.3	0.24	ND	2.1	1.5	0.57	0.1	ND	ND	0.7	0.8	0.79	0.92
	C18:1	22.14	41.9	22.4	35.8	63.5	63.42	65.8	61.6	69.5	26.91	27.2	63.19	ND	44.7	34.3	40.16	42.53
	C18:2	27.47	20.6	16.2	30.7	12.7	9.01	5.5	17.2	8.8	36.61	52.8	2.02	81.31	32.8	43.2	38.38	31.84
	C18:3	8.84	1.3	ND	1	ND	ND	0.2	1.4	0.4	0.75	1.8	ND	ND	0.2	0.2	ND	0.16
	Totals	58.46	64	38.6	67.5	76.5	72.67	71.5	82.3	80.2	64.84	82.2	65.21	81.31	78.4	78.5	79.33	75.45
References	[54]	[76]	[74]	[77]	[78]	[78]	[79]	[80]	[66]	[81]	[67]	[69]	[70]	[82]	[73]	[42]	[61]	

ND: Not Detected; a: yellow *Cyperus esculentus*; b: black *Cyperus esculentus*

## 6. Some fuel Properties of Biodiesels Obtained by Transesterification of Vegetable Oils

Compared to the diesel standards given in Table 4, only the viscosity of ethyl esters of *Cyperus esculentus* studied by

Barminas et al [65] is out of specification. Apart from the density and flash point of methyl esters from the processing of vegetable oil from *Huracrepitans* [59], all esters from vegetable oils of the other species investigated are within the limits recommended for diesel. Most fuel parameters (viscosity, density, pour point, cloud point, cetane number, etc.) of biodiesels comply with ASTM D6751 and EN 14214.

Table 4. Comparison of the fuel properties of some biodiesels with diesel standards.

Properties of biodiesels	<i>Adansonia digitata</i>	<i>Cyperus esculentus</i>	<i>Hura crepitans</i>	References	ASTM D6751 [84]	EN 14214 [84]
Kinematic viscosity (mm <sup>2</sup> /s)	ME: 4.46a ME: 0.859a' EE: 3.144a''	ME: 2.34; EE: 9.12b ME: 4.73b' ME: 4.48b''	ME: 3.95c ME: 2.78c' EE: 4.62c''	[54]a [62]a' [56]a'' [65]b [80]b' [83]b'' [67]c [59]c' [58]c''	1.90 – 6.00 <sup>1</sup>	3.50 – 5.00 <sup>1</sup>
Density	ME: 0.882a ME: 0.86a' EE: 0.855a''	ME: 0.866b; EE: 0.893b ME: 0.879b' ME: 0.882b''	ME: 0.86c ME: 0.92c' EE: 0.908c''	[54]a [62]a' [55]a'' [65]b [80]b' [83]b''	-	0.86 – 0.90 <sup>2</sup>

Properties of biodiesels	<i>Adansonia digitata</i>	<i>Cyperus esculentus</i>	<i>Hura crepitans</i>	References	ASTM D6751 [84]	EN 14214 [84]
Flash Point (°C)	ME: 192a ME: 170a' EE: 160a''	ME: 186b; EE: 200b ME: 178b'	ME: 152c ME: 112c' ME: 156c''	[67]c [59]c' [58]c'' [54]a [62]a' [55]a'' [65]b [56]b' [67]c [59]c' [60]c'' [54]a [62]a' [55]a''	≥ 93	≥ 120
Pour point (°C)	ME: -1a ME: 20a' EE: -1.50a''	ME: -3b	ME: 6c ME: -14c' EE: -1c''	(55)a'' [56]b [60]c [59]c' [58]c'' [54]a [62]a' [55]a''	-15 to 10	-
Cloud point (°C)	ME: 2a ME: 10a' EE: 6a''	ME: 13b	ME: 0c ME: 8c' EE: 5.90c''	[56]b [60]c [59]c' [58]c'' [54]a [62]a' [55]a''	-3 à 12	-
Oxidative stability (h) at 110°C	ME: 3.09a	ME: 5.50b' ME: 8.90b''	ME: 6.82c	[80]b' [83]b'' [67]c [54]a	-	≥ 6
Cetane number	ME: 57a	ME: 55.50b'	ME: 45.62c ME: 50.4c' ME: 50c''	[80]b' [67]c' [60]c'' [55]a''	≥ 47	≥ 51
Lower calorific value (MJ/Kg)	EE: 44.06a''	ME: 39.68b'	ME: 39.10c ME: 40.30c' ME: 37c''	[80]b' [67]c [59]c' [60]c'' [55]a'' [56]b	-	≥ 35
Acid value (mgKOH/g)	EE: 0.16a''	ME: 1.122b ME: 0.756b' ME: 0.50b''	ME: 0.21c ME: 2.34c' ME: 0.89c''	[80]b' [83]b'' [67]c [59]c' [68]c'' [56]b	≤ 0.50	≤ 0.50
Iodine Index (gI <sub>2</sub> /100g)	-	ME: 98.38b ME: 84.89b' ME: 82b''	ME: 127.50c ME: 116.40c'	[80]b' [83]b'' [60]c [59]c' [56]b	-	< 120
Ester (%)	-	ME: 82b; ME: 97.80b'; ME: 99.17b''	ME: 98.70c	[80]b' [83]b'' [67]c	-	≥ 96.50
Triglyceride (%)	-	ME: 0.015b'	ME: 0.10c	[67]c [80]b'	-	≤ 0.20
Diglyceride (%)	-	ME: 0.13b'	ME: 0.13c	[67]c [80]b'	-	≤ 0.20
Monoglyceride (%)	-	ME: 0.79b'	ME: 0.30c	[67]c [80]b'	-	≤ 0.80
Water content (%)	EE: 0.005a''	ME: 0.004b''	-	[55]a'' [83]b''	-	≤ 0.05

<sup>1</sup>Kinematic viscosity (mm<sup>2</sup>/s) at 40°C; <sup>2</sup>Density at 15°C; EE: Ethyl Ester; ME: Methyl Ester

The letters a, b and c refer to *Adansonia digitata*, *Cyperus esculentus* and *Hura crepitans* respectively.

The differences: a, a' and a'' are relative to the different authors; same for letters b and c.



## 7. Conclusion and Outlook

Vegetable oils are among the most important renewable energy sources. Their use as fuel in diesel engines, however, requires transformations in view of their physico-chemical parameters, which are often out of the norm. The physico-chemical parameters of the biodiesels obtained by the conversion of these oils are on the other hand very close to petrodiesel. They are less toxic, biodegradable, with high calorific values and their use reduces greenhouse gas emissions. Like interesterification, microemulsification, pyrolysis or dilution, basic or acid transesterification is the most widely used for converting vegetable oils into biodiesel because of its simplicity and low cost. To optimize the performance of this reaction, several parameters must be considered. These include: type, water content and quantity of alcohol used, type, nature and concentration of catalyst, reaction time and temperature, speed of agitation of reaction medium, water content of vegetable oil, etc. The fuel characteristics of methyl or ethyl esters (biodiesels) are largely the closest to those of petrodiesel compared to ASTM D6751 and EN 14214 for their use as a substitute for fossil diesel.

In order to bring the biodiesel sector closer to the local population, it will be necessary to adopt a more rational approach aimed at reducing the economic burdens inherent in the production of this bioresource. This could be effective through the use of distilled water for purification and thin layer chromatography to determine the ethyl ester yield of the biodiesel obtained. One could also think of a short or long term substitution of the base with an ethanolic solution of the ash from palm nut residues or cottonseed cake. The use of unconventional, neglected and underutilized oilseed species would also be an asset.

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