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Review

Biodiesel production from *Jatropha curcas*: A review

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Biodiesel has attracted considerable attention during the past decade as a renewable, biodegradable and non-toxic fuel alternative to fossil fuels. Biodiesel can be obtained from vegetable oils (both edible and non-edible) and from animal fat. *Jatropha curcas Linnaeus*, a multipurpose plant, contains high amount of oil in its seeds which can be converted to biodiesel. *J. curcas* is probably the most highly promoted oilseed crop at present in the world. The availability and sustainability of sufficient supplies of less expensive feedstock in the form of vegetable oils, particularly *J. curcas* and efficient processing technology to biodiesel will be crucial determinants of delivering a competitive biodiesel. Oil contents, physicochemical properties, fatty acid composition of *J. curcas* reported in literature are provided in this review. The fuel properties of *Jatropha* biodiesel are comparable to those of fossil diesel and confirm to the American and European standards. The objective of this review is to give an update on the *J. curcas L.* plant, the production of biodiesel from the seed oil and research attempts to improve the technology of converting vegetable oil to biodiesel and the fuel properties of the *Jatropha* biodiesel. The technological methods that can be used to produce biodiesel are presented together with their advantages and disadvantages. The use of lipase as biotechnological solution to alkali and acid catalysis of transesterification and its advantages is discussed. There is need to carry out research on the detoxification of the seed cake to increase the benefits from *J. curcas.* There is also need to carry out life-cycle assessment and the environment impacts of introducing large scale plantations. There is also still a dearth of research about the influence of various cultivation-related factors and their interactions and influence on seed yield. Many other areas that need to be researched on Jatropha curcas L. are pointed out in this review.

Key words: Biodiesel, transesterification, *Jatropha curcas*, fuel properties, vegetable oil.

INTRODUCTION

Biofuels are considered in part, a solution to such issues as sustainable development, energy security and a reduction of greenhouse gas emissions. Biodiesel, an environmental friendly diesel fuel similar to petro-diesel in comustion properties, has received considerable attention in the recent past worldwide. Biodiesel is a methyl or ethyl ester of fatty acid made from renewable biological resources such as vegetable oils (both edible and non-edible), recycled waste vegetable oil and animal fats (Demirbas, 2000; Kinney and Clemente, 2005; Wilson et al., 2005). The use of vegetable oils as alterative fuels has been around since 1900 when the inventor of the diesel engine Rudolph Diesel first tested peanut oil in his compression ignition engine (Shay, 1993). However, due to cheap petroleum products such non-conventional fuels never took off until recently. Biodiesel derived from surplus edible oils like soybean, sunflower and rapeseed oils is already being used in USA and Europe to reduce air pollution, to reduce dependence on depleting fossil fuel localised in specific regions of the world and increases in crude oil prices (Ma and Hanna, 1999; Sarin et al., 2007; Ranganathan et al., 2008; Agarwal, 2007; Berchmans and Hirata, 2008; Foidl et al., 1996; Openshaw, 2000; Meher et al., 2006). The use of edible oil to produce biodiesel in Africa and other developing continents is not feasible in view of a huge gap between demand and supply of such oils in the developing world. There is therefore, need to explore alternative non-edible oil for use in production of biodiesel.

However, in Asia and Africa, which are mostly net importers of vegetable oil, *Jatropha curcas* has been recognised as new energy crop for the countries to grow their own renewable energy source with many promising benefits. With the growing interest in biofuels worldwide, there is need for national governments in Africa to develop mechanisms for harnessing the potential of the fast growing industry and benefit from the growing international trade in biofuels. If Africa takes the lead in the production of biofuel, particularly from *Jatropha*, the continent's efforts in this endeavour will position it as an exporter of biodiesel, thus increasing its economic and political leverage in the global society. Many multinational companies, particularly Scandinavian, Chinese, European and Indian ones are scrambling for African land for *Jatropha* plantations. It is also reported that wireless communication giants Ericsson, GSMA and MTN are investing in using biofuel from *Jatropha* and other oils to power cellular network base stations in the developing world for the untapped market of the potential mobile users (Katembo and Gray, 2007).

The *J. curcas Linnaeus* plant originated from Mexico and was spread to Asia and Africa by Portuguese traders as a hedge plant. *J. curcas* L. belongs to the family Euphorbiaceae, which is renowned of having species that contravene the Geneva conventions on chemical warfare. The genus name Jatropha derives from the Greek *jatros* (doctor), *trophe* (food), which implies medicinal uses, hence the plant is traditionally used for medicinal purposes. It is a hardy shrub that can grow on poor soils and areas of low rainfall (from 250 mm a year) hence its being promoted as the ideal plant for small farmers (Sarin et al., 2007; Foidl et al., 1996; Gressel, 2008). Since Jatropha can grow relatively well in marginal areas compared to other traditional crops, it may help to reclaim degraded land and protecting the soil from soil erosion. The trees are easy to establish (from seeds or cuttings), grow relatively quickly (producing seed after their second year) and are hardy to drought. On average, each mature tree produces about four kilograms of seed per year when cultivated under optimal conditions. It has a long productive period of around 30 - 50 years (Banapurmath et al., 2008; Tamalampundi et al., 2008).

The proximate analysis of *Jatropha* seeds revealed that the percentage of crude protein, crude fat and moisture were 24.60, 47.25 and 5.54% respectively (Akintayo, 2004). The seeds can be transported without deterioration and at low cost due to its high specific weight. The seeds of the *Jatropha* contain 30 - 40% oil that can be easily expressed for processing (transesterification) and refinement to produce biodiesel (Akintayo, 2004; Gubitz et al., 1999; Mahanta et al., 2008). *J. curcas* gives higher oil yield per hectare than peanuts, sunflower, soya, maize or cotton when grown under optimum conditions. The processed oil can be used directly in diesel engines after minor modifications or after blending with conventional diesel. The fact that the oil of *J. curcas* cannot be used for nutritional purposes without detoxification makes its use as an energy source for fuel production very attractive. The byproducts of the biodiesel processing plant are nitrogen-rich press cake and glycerol, which are said to have good commercial value as fertiliser and as a base for soap and cosmetics, respectively. Makkar et al. (1998) found that crude protein was 56% in Cape Verde, 61% in Nicaragua, 56% in Ife-Nigeria and 64% in non-toxic Mexico *J. curcas* varieties. They also found that the amino acid composition of meals of non-toxic variety and toxic varieties was high and similar and the levels of essential amino acids except lysine were comparable with that for FAO reference protein. *J. curcas* is traditionally used for medicines and as hedges to protect fields and gardens since animals do not eat it (Gubitz et al., 1999; Mampane et al., 1987; Joubert et al., 1984; Staubamann, et al., 1999). The leaves, root and bark also have potential for numerous other industrial and pharmaceutical uses as shown in Figure 1. A number of enzymes such as protease, lipase and esterase with good properties for use in biotechnology have also been extracted and purified from *J. curcas* L. (Staubamann et al., 1999; Nath et al., 1991). These features have generated a great interest in the *Jatropha* plant which is now becoming a cash crop in South and Central America, Europe, Africa and Asia. Table 1 summarises some of the benefits and disadvantages of *J. curcas* production. The positive claims on *J. curcas* are numerous, but only a few of them can be scientifically sustained.

Information on cultivation, establishment, management and productivity of Jatropha under various climatic conditions is lacking in peer-reviewed literature. *J. curcas* L. belongs to the family Euphorbiaceae, which is renowned of having species that contravene the Geneva conventions on chemical warfare. Research has indicated that *J. curcas* oil-producing seeds are toxic to humans and most animals and birds hence its commonly referred to as "Black vomit nut", "Purge nut", "Physic nut", "Pinoncillo", "American purging nut", "Barbados purging nut", "poison nut tree" the "graveyard tree", etc (Akintayo, 2004; Gubitz et al., 1999). *J. curcas* L. is actually a tree known by more than 200 multi-language names (Katembo and Gray, 2007). Its oil is commonly known as hell oil, oil infernale (Makkar, et al., 1998; Gubitz, et al, 1999; Staubamann et al., 1999). Indeed the seed and/ oil were found to be toxic to mice (Adams, 1974), rats (Liberalino et al., 1988), calves, sheep and goats (Ahmed and Adam, 1979a, b), humans (Rai and Lakhanpal, 2008; Mampane et al., 1987; Abdu-Aguye et al., 1986; Koltin et al., 2006), chickens (Samia et al., 1992). Recent *J. curcas* poisoning in pediatric patients was reported in Mauritius where a total of eleven cases of pignon d'Inde poisoning due to consumption of Jatropha seeds was reported in one day (Rai and Lakhanpal, 2008). The reason for consumption was the attractive shapes of nuts of the plant which closely resemble cashew fruit though it bears no relationship to the latter. Toxicity of *J. curcas* seeds is generally attributed to the presence of lectin in these

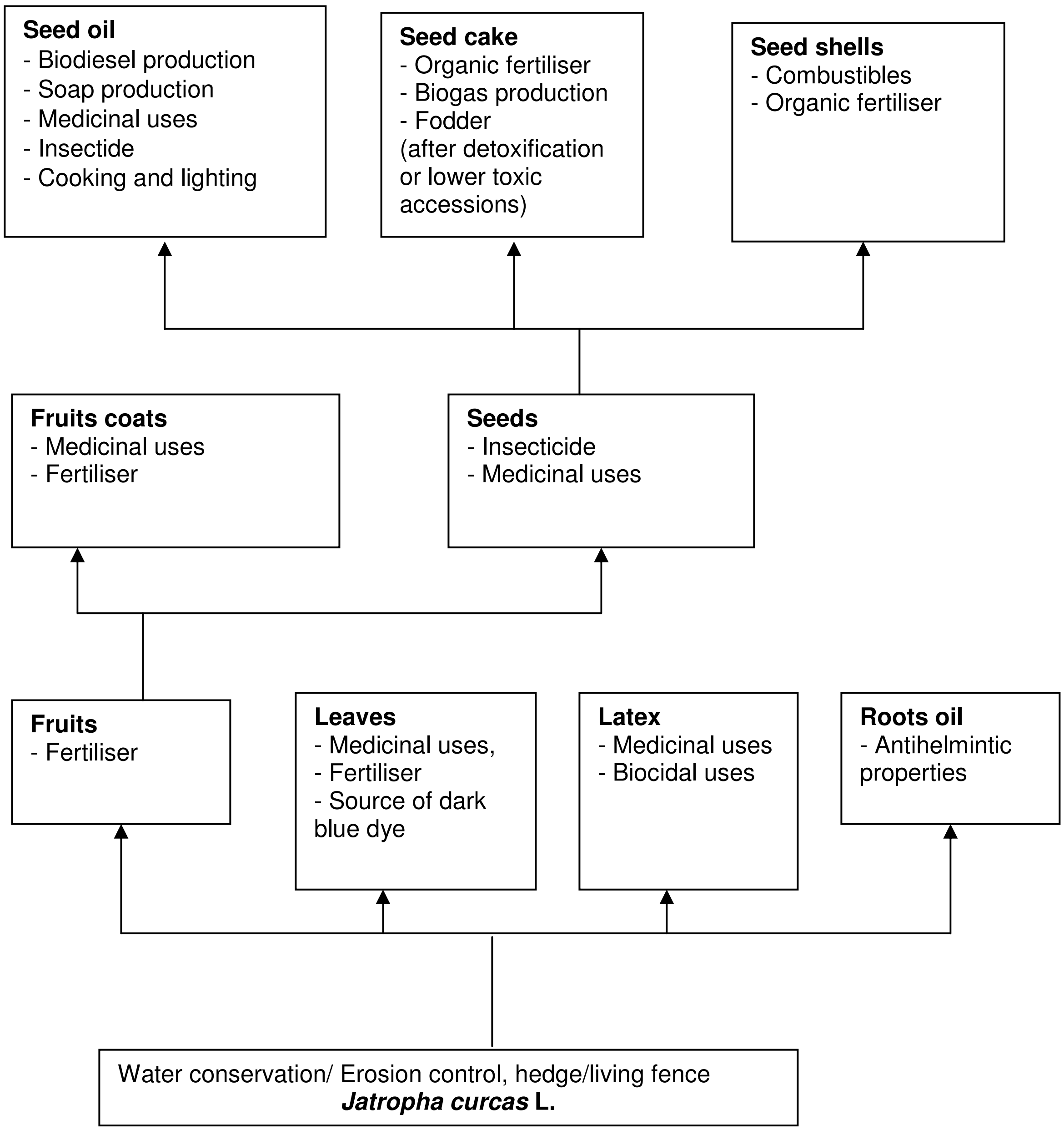

Figure 1. The various uses of *J. curcas* components (adapted from Jones and Miller, 1991).

seeds (Samia et al., 1992). The fruits contain irritants which affect pickers and those who remove the seeds by hand. However, similar lectin values found in non-toxic Mexico and the toxic Cape verde and Nicaragua varieties suggested that lectin is not the main toxic principle in *Jatropha* seeds (Makkar et al., 1998). The seeds are poisonous because they contain toxalbumine called curcine, cyanic acid related to ricinic acid, and toxic phorbol esters (Nath and Dutta, 1991; Adolf et al., 1984; Levin et al., 2000; Rai and Lakhanpal, 2008). Toxicoses are reported in the medical literature and ingesting four seeds can be toxic to a child, with symptoms resembling organophosphate insecticide intoxication, yet with no antidote for the lethal mixture (Abdu-Aguye et al., 1986; Gubitz et al., 1999; Joubert et al., 1984; Koltin et al., 2006). Phorbol esters were found to be responsible for purgative, skin-irritant effects and tumour promotion (Adolf et al., 1984; Hirota et al., 1988).

The leaves contain the flavonoids apigen and its glycosides vitexin and isovitexin, the sterols stigmasterol, β-D-sitosterol and its β-D-glucoside (Mampane et al., 1987). In addition, *J. curcas* leaves contain steroid sapogenins, alkaloids, the triterpenalcohol 1-triacontanol ($C_{30}H_{62}O$) and a dimmer of a triterpenalcohol ($C_{63}H_{117}O_9$). 12-Deoxy-10-hydroxyphorbol, a polyunsaturated diterpene ester was isolated from the seed oil of *J. curcas* which is an irritant and purgative (Adolf et al., 1984).

The extraction of biocrude oil from the *Jatropha* seeds

Table 1. The potential advantages and disadvantages of *J. curcas* L. plant.

The advantages of Jatropha plant
Good agronomic traits
1. Hardy shrub which grows in semi-arid conditions and poor soils
2. Can be intercropped with high value crops such as sugar, coconut palm, various fruits and vegetables, providing protection from grazing livestock and phyto-protection action against pests and pathogens
3. It is easy to establish and grows relatively quickly.
4. Yields around 4 tonnes of seed per hectare in unkept hedges are achievable
5. Has low nutrient requirements
6. Requires low labour inputs
Multi-purpose plant
1. Protective hedges around fields
2. Reclaims marginal soils
3. Non-edible and therefore does not compete with food supply when used for biodiesel production
4. Is energy crop that produce seeds with high oil yields
The disadvantages of Jatropha
Seeds and leaves are toxic to human beings and animals
Toxicity is based on several components (phorbol esters, curcains, trypsin inhibitors and others) which make complete detoxification a complicated and difficulty process.
Competes with food production for land use

is expected to generate huge quantities of residual deoiled seed cake. Jatropha production is forecasted at about 2500 kg seeds per hectare under Indian conditions (Hirota et al., 1988). Considering 40 - 50% oil in the seeds, the extraction will generate approximately 1000 kg seed cake per hectare crop. The *J. curcas* nitrogen-rich press cake by-product is very toxic and cannot be used as animal feed without first having been detoxified. The toxicity of *J. curcas* is based on several components such as phorbol esters, curcains, trypsin inhibitors and others that are present in considerable amounts in all plant components which make complete detoxification a difficulty and complicated process. The best extraction procedures available for the removal of phorbol esters remove about half, which is unacceptable toxicologically in accessions with high initial content (Haas and Mittelbach, 2000; Martinez et al., 2006; Makkar et al., 1997). Detoxification has only been successful at laboratory scale but since the process is complicated, it is not suitable for small and large scale and local use. For animal feed, the seed cake must be detoxified completely, and constantly with quality guaranteed and therefore, it is expected to be expensive. If the seed cake could be detoxified and could be used as animal feed, the benefits of the *Jatropha* projects will be increased significantly (Mahanta et al., 2008). At present, the successful penetration of J*atropha* seed cake as animal feed to the market at a profitable price seems doubtful. There is need to research on the detoxification of the seed cake to increase the benefits from *J. curcas.* There are now many concerns regarding the cultivation of the *J. curcas* tree both at small-scale and large-scale in the world without due consideration of its impact on ecology, food production and the environment. The tree has an invasive potential through seed dispersal. Due to its perceived benefits, the growing of the *J. curcas* is shifting from small-scale farmers to tight-controlled corporate production either on large plantations or through stringent contract production in India, Burma, Saudi Arabia, Malaysia, Indonesia, Philippines, China, Ghana, South Africa, Senegal, Nigeria, Tanzania, Ethiopia, Zambia and Zimbabwe among other countries. Introducing an alien species at large scale in the environment, even if it can potentially contribute to rural employment and poverty alleviation, needs serious consideration. The claimed tolerance of *J. curcas* to pests and diseases on few dispersed trees might not apply in general to trees in plantations. Indeed *Jatroph*a can grow in the semi-arid lands but may be without any commercial yield being achieved. There is increasing evidence that seed yields are sensitive to soil fertility and moisture availability. According to Foidl et al. (1996) the predictions of productivity seem to ignore the results of plantations from the 1990s, most of which are abandoned now for reasons of lower productivity and or higher labour costs than expected. There is still lack of knowledge on its potential yield under sub-optimal and marginal conditions making it difficult to predict yields from planned plantations under sub-optimal growth conditions, the conditions where *J. curcas* is supposed to prove its value.

Most recent published of low production figures mostly apply to young *J. curcas* plantations of 1 - 2 years old. Some authorities predict yields ranging from 0.6 - 15 tonnes seed per hectare per year under proper conditions of crop establishment, water and fertility levels. Depending on crop growth conditions, such as water, soil fertility and absence of disease, maximum yields of 7.8 tonnes seed per hectare are predicted for mature stands. The seed yield and seed oil yield varies widely which is logic for a crop that grows under many different conditions. Genetic and environmental factors have a significant on oil yield production factors. *J. curcas* is still a wild species and genetic identification of provenances and testing them in different locations and conditions still need to be done. There is also still a dearth of research about the influence of various cultivation-related factors and their interactions and influence on seed yield. Projections of seed yield and oil yield on plantations in many websites lack a sound scientific basis with wide variations and do not give description of conditions under which data were collected (Openshaw, 2000).

It may not be true that Jatropha oil production requires minimum amounts of labour because labour is required to prepare the land, set-up nurseries, plant, irrigate, fertilise, prune, harvest and process the seeds ready for the market, particularly in the early years. It is expected that labour for maintenance and harvest should increase to substantial levels in subsequent years. Otherwise minimum labour is only required only if *J. curcas* is grown for combating desertification and preventing soil erosion.

The global expansion of biofuels production will have serious ramifications for Africa, which has large land mass and favourable climate for growing energy crops. There is need for proper policies and mechanisms to regulate the sector to ensure that biofuels such as Jatropha are not given too much priority at the expense of other important values for nature, environment and society. Of particular concern is the competition for land, water and the displacement of land for the cultivation of food and other crops. The production of energy crops such as Jatropha in Africa might be so attractive in terms of income that may induce the diversion of resources away from food production for biofuels thereby threatening food security. An influx of large investors could also lead to undesirable competition with food crops. Farmers could be induced to become out growers of large buyers, converting too much prime crop land to *Jatropha* cultivation or worse still induced to sell their land to large investors.

There is still a significant amount of research that needs to be done on *Jatropha* before it could become a dominant and sustainable source of biodiesel. The actual breeding and development of the genetic resources of *Jatropha* are quite at an early stage. There is need to know far more about the different genotypes and varieties of *Jatropha* around the world, and whether there is a large amount of genetic variation that can be used to develop *Jatropha* crops for different geographical locations. The genus *Jatropha* contains approximately 170 known species (Katembo and Gray, 2007).

The direct usage of this vegetable oil (triglyceric esters) as biodiesel is possible but unsatisfactory for long term usages in today's direct and indirect diesel engines (Ma and Hanna, 1999; Ranganathan et al., 2007). This is because they have high viscosity, are contaminated by acid, and form gum due to oxidation and polymerisation of free fatty acids during storage and combustion, deposit of carbon on engines and thickening of lubricating oil. Therefore, vegetable oils are processed so as to acquire viscosity and volatility characteristics similar to fossil fuels (Agarwal, 2007).

PROCESSING TECHNIQUES

Natural vegetable oils and animal fats are pressed to obtain crude oil which contains free fatty acids, phospholipids, sterols, water, odorants and other impurities (Openshaw, 2000). Because of these compounds, high viscosity, low volatility and the polyunsaturated character of the vegetable oils, they cannot be used as fuel directly in compression engines (Banapurmath et al., 2008; Srivastava and Prasad, 2000). The specifications of the seed oil of *J. curcas* are outlined in Table 2 and the fatty acid composition of the seed oil of *J. curcas* is compared with other vegetable oils in Table 3. Jatropha seed oil has about 72% unsaturated fatty acids with oleic acid predominatly followed by lenoleic acid. The viscosity of *Jatropha* oil is considerably lower than those reported for some common and tested oils at 30°C such as soybean (31cSt), cottonseed (36cSt), and sunflower (43cSt) and pointing to its suitability for use as diesel fuel (Akintayo, 2004; Kamman and Phillip, 1985).

To overcome the problems highlighted above of using the vegetable oils directly, the oils require chemical modification so that they can match the properties of fossil diesel. The processing techniques that are mainly used to convert vegetable oils including *Jatropha* oil into fuel form are direct use and blending, pyrolysis, microemulsification and transesterification (Demirbas, 2000; Ma and Hanna, 1999; Nwafor, 2003). Although production of biodiesel is a mature technology, there is still a lot ongoing research to improve the quality and yield of the biodiesel from vegetable oils.

Direct use and blending

In 1900 Dr Diesel demonstrated his engine running on 100% peanut oil at World Exhibition in Paris. Caterpillar (Brazil) in 1980 used pre-combustion chamber engines with a mixture of 10% vegetable oil to maintain total power without any modifications to the engine (Agarwal, 2007). A mixture of degummed soybean oil and No. 2 diesel fuel in the ratio 1:2 did not cause lubricating oil thickening and gelling unlike a 1:1 ratio when tested for engine performance and crankcase lubricant viscosity in a John Deere 6-cylinder, 6.6 L displacement, direct-injection,

Table 2. Specifications of the seed of the seed oil of *J. curcas* (Foidl et al., 1996; Tamalampundi et al., 2008).

Variable	Variety Caboverde	Variety Nicaragua	Variety Nigeria
Colour	**Light yellow**	**Light yellow**	**Light yellow**
Saponification number (mg/g)	192	190	199
Viscosity at 30°C (cSt)	39	37	17
Free fatty acids (% weight)	0.3-0.4	0.6-1.3	1.8
Unsaponifiable (% weight)	1.1	0.8	0.8
Iodine number	95	107	105
Acid value	–	–	3.5
Specific gravity (25°C)	–	–	0.92

Table 3. Fatty acid composition (%) of the seed oil of *J. curcas* compared with other vegetable oils (Ma and Hanna, 1999; Sarin et al., 2007; Foidl et al., 1996).

Fatty acid	*J. curcas* Caboverde	*J. curcas* Nicaragua	Soybean	Cotton seed	Palm	Sunflower
Capric	0.1	0.1	–	–	–	–
Myristic	0.1	0.1	0.1	0.7	1.0	0.2
Palmitic	15.1	13.6	10.2	20.1	42.8	4.8
Palmtoleic	0.9	0.8	0.1	–	–	0.8
Stearic	7.1	7.4	3.7	2.6	4.5	5.7
Oleic	44.7	34.6	22.8	19.2	40.5	20.6
Linoleic	31.4	43.2	53.7	55.2	10.1	66.2
Linolenic	0.2	0.2	8.6	0.6	0.2	0.8
Arachidic	0.2	0.3	0.3	–	–	0.4
Behenic	0.2	–	0.1	–	–	–
Lauric	–	–	0.1	0.1	0.1	0.5

turbo charged for a total 600 h (Adams et al., 1983). Pramanik et al. (2003) found that 50% blend of *Jatropha* oil could be used in diesel engine without any major operational difficulties but further study is needed on the long term effect on engine. However, direct use of vegetable oils and their blends have generally been considered to be unsatisfactory and difficult to use in both direct and indirect diesel engines. The obvious problems are the high viscosity, acid composition, free fatty acid content, as well as gum formation due to oxidation, polymerisation during storage and combustion, oil ring sticking, carbon deposits and thickening or gelling of lubricating oil and other problems (Ma and Hanna, 1999; Agarwal, 2007; Meher et al., 2006; Engler et al., 1983; Nath and Dutta, 1989; Peterson, 1986).

Micro-emulsion

The problem of the high viscosity of vegetable oils was solved by micro-emulsions with solvents such as methanol, ethanol, and 1-butanol (Agarwal, 2007). A micro-emulsion is defined as a colloidal equilibrium dispersion of optically isotropic fluid microstructures with dimensions generally in the 1 - 150 nm range formed spontaneously from two normally immiscible liquids and one or more ionic or non-ionic amphiphiles (Ma and Hanna, 1999). The components of a biodiesel micro- emulsion include diesel fuel, vegetable oil, alcohol, and surfactant and cetane improver in suitable proportions. Alcohols such as methanol and ethanol are used as viscosity lowering additives, higher alcohols are used as surfactants and alkyl nitrates are used as cetane improvers. Micro-emulsions can improve spray properties by explosive vaporisation of the low boiling constituents in the micelles. Micro-emulsion results in reduction in viscosity increase in cetane number and good spray characters in the biodiesel. According to Srivastava and Prasad (2000), short term performance of micro-emulsions of aqueous ethanol in soybean oil was nearly as good as that of No. 2 diesel, despite the lower cetane number and energy content.

However, continuous use of micro-emulsified diesel in engines causes problems like injector needle sticking, carbon deposit formation and incomplete combustion.

Pyrolysis (thermal cracking)

Pyrolysis can be defined as the conversion of one substance into another by means of heat in the absence of air (or oxygen) or by heat in the presence of a catalyst which result in cleavage of bonds and formation of a variety of small molecules. The pyrolysis of vegetable oil to produce biofuels has been studied and found to produce alkanes, alkenes, alkadienes, aromatics and carboxylic acids in various proportions (Ma and Hanna, 1999; Alencar et al., 1983; Peterson, 1986). The equipment for thermal cracking and pyrolysis is expensive for modest biodiesel production particularly in developing countries. Furthermore, the removal of oxygen during the thermal processing also removes any environmental benefits of using an oxygenated fuel (Ma and Hanna, 1999). Another disadvantage of pyrolysis is the need for separate distillation equipment for separation of the various fractions. Also the product obtained was similar to gasoline containing sulphur which makes it less eco-friendly (Ranganathan et al., 2007).

Transesterification (alcoholysis)

Transesterification of vegetable oils is the most popular method of producing biodiesel. Transesterification (alternatively alcoholysis) is the reaction of a fat or oil (trigylceride) with an alcohol to form fatty acid alkyl esters (valuable intermediates in oleo chemistry), methyl and ethyl esters (which are excellent substitutes for biodiesel) and glycerol as shown:

$$
\begin{array}{llll}
CH_2\text{-}OOC\text{-}R_1 & & R_1\text{-}COO\text{-}R' & CH_2\text{-}OH \\
| & & & | \\
CH\text{-}OOC\text{-}R_2 + 3R'OH & \rightleftarrows & R2\text{-}COO\text{-}R' + & CH\text{-}OH \\
| & & & | \\
CH_2\text{-}OOC\text{-}R_3 & & R_3\text{-}COO\text{-}R' & CH_2\text{-}OH
\end{array}
$$

Triglyceride Alcohol Esters Glycerol

(Vegetable oil)

Transesterification as an industrial process is usually carried out by heating an excess of the alcohol with vegetable oils under different reaction conditions in the presence of an inorganic catalyst. The reaction is reversible and therefore excess alcohol is used to shift the equilibrium to the products side. The alcohols that can be used in the transesterification process are methanol, ethanol, propanol, butanol and amyl alcohol, with methanol and alcohol being frequently used. The reactions are often catalysed by an acid, a base or enzyme to improve the reaction rate and yield. Alkali-catalysed transesterification is much faster than acid-catalysed transesterification and is most often used commercially (Ma and Hanna, 1999; Ranganathan et al., 2008; Agarwal and Agarwal, 2007). The alkalis which are used include sodium hydroxide, potassium hydroxide, and carbonates. Sulphuric acid, sulfonic acids, and hydrochloric acids are the usual acid catalysts. After transesterification of trigylcerides, the products are a mixture of esters, glycerol, alcohol, catalyst and tri-, di- and monogylcerides which are then separated in the downstream (Ma and Hanna, 1999; Freedman et al., 1986; Demirbas, 2005).

The process of transesterification brings about drastic change in viscosity of the vegetable oil. The high viscosity component, glycerol, is removed and hence the product has low viscosity like the fossil fuels. The biodiesel produced is totally miscible with mineral diesel in any proportion. Flash point of the biodiesel is lowered after transesterification and the cetane number is improved. The yield of biodiesel in the process of transesterification is affected by several process parameters which include; presence of moisture and free fatty acids (FFA), reaction time, reaction temperature, catalyst and molar ratio of alcohol and oil.

The effect of moisture and free fatty acids

The gylceride should have an acid value less than 1 and all materials should be substantially anhydrous. An acid value greater than 1 requires that the process uses more sodium hydroxide to neutralise the free fatty acids. Transesterification yields are significantly reduced if the reactants do not meet this requirement (Freedman et al., 1986; Goodrum, 2002; Dorado et al., 2002; Ma et al., 1998). The presence of water causes the transesterification reaction to partially change to saponification, which produces soap and thus lowering the yield of esters. Saponification also renders the separation of ester and glycerol difficult since it increases the viscosity and form gels (Berchmans and Hirata, 2008).

Most of the biodiesel is currently made from edible oils by using methanol and alkaline catalyst. However, there are large amounts of low cost oils and fats that cannot be converted to biodiesel using methanol and alkaline catalyst because they contain high amounts of free fatty acids and water. In some instances, crude *J. curcas* oil quality gradually deteriorates due to improper handling and inappropriate storage conditions which cause various chemical reactions such as hydrolysis, polymerisation and oxidation to occur. Improper handling and prolonged exposure of crude *J. curcas* oil will result in an increase in the concentration of free fatty acids and water. The presence of high concentration of free fatty acids can significantly reduce the yield of methyl esters. Two-step process, acid-catalysed esterification process and followed by base-catalysed transesterification process have been developed for these oils in which initially the free fatty acids are converted to fatty acid methyl esters by an acid catalysed pretreatment and then transesterified using alkaline catalyst in the second step (Berchmans and Hirata, 2008; Ghadge and Raheman, 2005; Velkovic et al., 2006). A two-stage transesterification process for crude *J. curcas* L. seed oil with high content of free fatty acids was studied by Berchmans and

Hirata (2008). The first stage was acid pretreatment process which reduced the free fatty level to less than 1%. The second stage, alkali base catalysed transesterification process gave 90% methyl ester yield.

The effect of reaction time

The conversion rate increases with reaction time and therefore is important in the transesterification process. Freedman et al. (1986) studied the transesterification of peanut, cotton-seed, sunflower and soybean oils under methanol to oil ratio of 6:1, 0.5% sodium methoxide catalyst and 60°C. About 80% yield was observed after 1 minute for soybean and sunflower oils. After an hour, yields (93 - 98%) were almost the same for the four oils. Similar results were reported by Ma et al. (1998). No similar studies have been reported for *J. curcas* oil.

The effect of reaction temperature

The transesterification process can occur at different temperature depending on the oil used. Generally the reaction is carried out close to the boiling point of methanol (60 - 70°C) at atmospheric pressure at molar ratio (alcohol to oil) of 6:1 (Srivastava and Prasad, 2000; Pramanik, 2003; Huaping et al., 2006). Freedman et al. (1984) observed that temperature clearly influenced the reaction rate and yield of esters when they investigated transesterification of soybean oil with methanol (6:1) at 32, 45 and 60°C.

The effect of molar ratio

The stoichiometric ratio for transesterification requires 3 mole of alcohol per mole of triglyceride to yield 3 mole fatty esters and 1 mole of glycerol. The transesterification reaction is shifted to the right by using excess alcohol or removing one of the products from the reaction mixture continuously. A molar ratio of 6:1 (with alkali as the catalysts) is normally used in industrial processes to obtain yields of methyl esters higher than 98% by weight. Ratios greater than 6:1 do not increase the yield but rather interfere with separation of glycerol because there is an increase in glycerol solubility. When glycerine remains in solution, it helps drive the equilibrium back to the left, lowering the yield of esters (Tomasevic and Marinkovic, 2003). When using acid catalyst the desirable product is obtained with 1 mol% of sulphuric acid with molar ratio of 30:1 at 65°C and conversion of 99% is achieved in 50 h.

The effect of catalysts

To make the transesterification process possible a catalyst in the form of an alkali, acid or lipase enzyme is required.

Alkali catalyst

Alkali-catalysed transesterification is much faster than acid-catalysed transesterification and is less corrosive to industrial equipment and therefore is the most often used commercially (Ma and Hanna, 1999; Ranganathan et al., 2008; Agarwal, 2007; Marchetti et al., 2007). Sodium hydroxide or potassium hydroxide is used as basic catalyst with methanol or ethanol as well as the vegetable oil. Sodium hydroxide is cheaper and is the widely used in large scale-processing. The alkaline catalyst concentration in the range of 0.5 - 1% by weight yield 94 - 99% conversion of most vegetable oils into esters. There are several disadvantages in using an alkaline catalysis process although it gives high conversion levels of triglycerides to their corresponding methyl esters in short reaction times. The process is energy intensive, recovery of glycerol is difficult, the alkaline catalyst has to be removed from the product, alkaline wastewater generated requires treatment and the level of free fatty acids and water greatly interfere with the reaction. The risk of free acid or water contamination results in soap formation that makes the separation process difficult (Fukuda et al., 2001; Barnwal and Sharma, 2005).

Acid catalyst

The second conversional way of making the biodiesel is to use the triglycerides with alcohol and an acid. Sulphuric acid, sulfonic acids, and hydrochloric acids are the usual acid catalysts but the most commonly used is sulphuric acid. Acid catalysts are used if the trigylceride has a higher free fatty acid content and more water. Although the yields could be high, the corrosiveness of acids may cause damage to the equipment and the reaction rate can be low, sometimes taking more than day to finish (Freedman et al., 1984). According to some authors, the reactions are also slow, requiring typically temperature above 100°C and more than 3 h to complete the conversion (Meher et al., 2006). For example, Freedman et al. (1986) studied the transesterification of soybean oil in the presence of 1% sulphuric acid with alcohol/oil molar ratio 30:1 at 65°C and the conversion was completed in 20 h.

Heterogeneous catalysts

Heterogeneous catalysts such as amorphous zirconia, titanium and potassium zirconias have also been used for catalysing the transesterification of vegetable oils. Huaping et al. (2006) demonstrated the potential of

Table 4. The advantages and disadvantages of using lipases.

The advantages of using lipases
1. Biocompatible, biodegradable and environmental acceptability,
2. Possibility of regeneration and reuse of the immobilised residue, because it can be left in the reactor if one keep the reactive flow,
3. Use of enzymes in reactors allows use of high concentration of them and that makes for a longer activation of the lipases,
4. immobilisation of lipase could protect it from the solvent that could be used in the reaction and that will prevent all enzyme particles getting together,
5. Separation of product will be easier using this catalyst, producing product of very high purity with less or no downstream operations
Some disadvantages
1. Loss of some initial activity due to volume of the oil molecule.
2. Number of support enzyme is not uniform
3. Biocatalyst is more expensive

preparing biodiesel from *J. curcas* oil catalysed by solid super base of calcium oxide and its good refining process. When treated with ammonium carbonate solution and calcinated at high temperature, calcium oxide becomes a solid super base, which shows high catalytic activity in transesterification. Under the optimum conditions, the conversion of *J. curcas* oil can reach 93%. The heterogeneous catalyst eliminates the additional cost associated with the homogeneous sodium hydroxide to remove the catalyst after transesterification.

Lipase catalyst-a biotechnological approach

Recently, enzymatic transesterification has attracted much attention for biodiesel production as it produces high purity product (esters) and enables easy separation from the by-product, glycerol (Devanesan et al., 2007; Mamoru et al., 2001; Oznur and Melek, 2002; Ranganathan et al., 2008). The enzyme that was found to be capable of catalysing transesterification is lipase. Lipase can be obtained from microorganisms like *Mucor miehei*, *Rhizopus oryzae*, *Candida antarctica, Pseudomonas fluorescens* and *Pseudomonas cepacia*. Enzymatic biodiesel production is possible using both intracellular and extracellular lipases. Biocompatibility, biodegradability and environmental acceptability of the biotechnological procedure when using lipase as a catalyst are the desired properties in this alternative biodiesel production method (Marchetti et al., 2007; Devanesan et al., 2007). However, the use of extracellular lipase as a catalyst requires complicated recovery, purification and immobilisation processes for industrial application (Bank et al., 2001). Consequently, the direct use of whole cell biocatalyst of intracellular lipases has received considerable research efforts (Devanesan et al., 2007; Kaieda et al., 1999; Matsumoto et al., 2001). For the industrial transesterification of fats and oils, *Pseudomonas* species immobilised with sodium alginate gel can be used directly as a whole cell bio-catalyst (Foidl et al., 1996; Devanesan et al., 2007; Mohamed and Uwe, 2003; Yong and Siyi, 2007). Devanesan et al. (2007) reported maximum yield (72%) of biodiesel from transesterification of *Jatropha* oil and short chain alcohol (methanol on hexane) using immobilised *P. fluorescens* at the optimum conditions of 40°C, pH 7.0, molar ratio of 1:4, amount of beads of 3 g and reaction time of 48 h.

In all the work in literature on lipases, the enzymes or whole cells are immobilised and used for catalysis. The advantage of immobilisation is that the enzyme can be reused without separation. Also the operating temperature of the process is low (50°C) compared to other techniques which operate at harsh conditions. However, the cost of enzymes remains a barrier for its industrial implementation (Neslon et al., 1996; Shimada et al., 2002). In order to increase the cost effectiveness of the enzymatic process, the enzyme (both intracellular and extracellular) is reused by immobilising in a suitable biomass support particle and that has resulted in considerable increase in efficiency (Ranganathan et al., 2008, Neslon et al, 1996; Jackson and King, 1996). The advantages and disadvantages of using lipases are summarised in Table 4. Various alcohols are being investigated for the transesterification process using lipase including methanol, ethanol, *iso*-propanol and butanol.

Jackson and King (1996) used immobilised lipases as biocatalysts for transesterification of corn oil in flowing supercritical carbon dioxide and reported an ester conversion of more than 98%. But the activity of immobilised enzyme is inhibited by methanol and glycerol present in the mixture. The use of *tert*-butanol as a solvent, continuous removal of glycerol, stepwise addition of methanol are found to reduce the inhibitory effects, thereby increasing the cost effectiveness of the process (Li et al., 2006; Samukawa et al., 2000; Royon et al., 2007).

Effective methanolysis using extracellular lipase has been reported to improve by stepwise addition of methanol through which 90 - 95% conversion can be achieved even after 50 and 100 cycles of repeated

Table 5. Comparison of the different technologies to produce biodiesel.

Variable	Alkali catalysis	Acid catalysis	Lipase catalysis
Reaction temp (°C)	60-70	55-80	30-40
Free fatty acid in raw materials	Saponified products	Esters	Methyl esters
Water in raw materials	Interference with reaction	Interference with reaction	No influence
Yields of methyl esters	Normal	Normal	Higher
Recovery of glycerol	Difficult	Difficult	Ease
Purification of methyl esters	Repeated washing	Repeated washing	None
Production cost of catalyst	Cheap	Cheap	Relatively expensive

Table 6. Fuel properties of *Jatropha* oil, *Jatropha* biodiesel and fossil diesel (Kamman and Phillip, 1985; Matsumoto et al., 2001; Ban et al., 2001).

Property	*J.* oil	*J.* biodiesel	Diesel	Biodiesel standards	
				AST D 6751-02	DIN EN 14214
Density (15°C, kgm^{-3})	940	880	850	–	860-900
Viscosity (mm^2s^{-1})	24.5	4.8	2.6	1.9-6.0	3.5-5.0
Flash point (°C)	225	135	68	>130	>120
Pour point (°C)	4	2	–20	–	–
Water content (%)	1.4	0.025	0.02	<0.03	<0.05
Ash content (%)	0.8	0.012	0.01	<0.02	<0.02
Carbon residue (%)	1.0	0.20	0.17	–	<0.30
Acid value ($mgKOHg^{-1}$)	28.0	0.40	–	<0.80	<0.50
Calorific value ($MJkg^{-1}$)	38.65	39.23	42	–	–

operation (Shimada et al., 2002; Samukawa et al., 2000; Watanabe et al., 2000). The efficiency of transesterification process using lipase can be significantly increased by using intracellular lipase (whole cell immobilisation) instead of extracellular lipase which demands complex purification stages before immobilisation. This can clearly reduce cost of the transesterification production as reported by Matsumoto et al. (2001), Ban et al. (2001) and Hama et al. (2004), when *R. oryzae* for the transesterification process of vegetable oils was used. Tamalampudi et al. (2008) recently reported that whole cell *R. oryzae* immobilised onto bio-mass support particles which catalysed the methanolysis of *Jatropha* oil more efficiently than Novozym 435.

The production of biodiesel using a biocatalyst eliminates the disadvantages of the alkali process by producing product of very high purity with less or no downstream operations (Meher et al., 2006; Fukuda et al., 2001; Modi et al., 2007). The process of producing biodiesel using immobilised lipase has not yet been implemented at industrial scale. On the other hand, in general the production cost of a lipase catalyst is significantly greater than that of an alkaline one. There are no comparative studies in the literature on the most appropriate transesterification technique which can be used to produce biodiesel from *J. curcas* L. The advantages and disadvantages of the methods of transesterification are summarised in Table 3.

FUEL PROPERTIES OF *JATROPHA* BIODIESEL

The fuel properties of *Jatropha* biodiesel are summarised in Table 5. *Jatropha* biodiesel has comparable properties with those of fossil biodiesel and conforms to the latest standards for biodiesel. Standardisation is a prerequisite for successful market introduction and penetration by biodiesel, and many countries including Austria, Germany (DIN), Italy, France, United States (AST D) have defined standards for biodiesel.

APPLICATIONS OF BIODIESEL IN COMBUSTION ENGINES

The properties of *Jatropha* oil, *Jatropha* biodiesel and fossil diesel are compared in Table 6. The high viscosity of vegetable oils leads to problems in pumping and spray characteristics when used in combustion engines. The best way to use the vegetable oils as fuel in compression ignition engines is to convert it into biodiesel. Biodiesel can be blended in various proportions with fossil diesel to

Table 7. The advantages and disadvantages of biodiesel fuel.

Advantages of biodiesel
1. Provides a domestic, renewable energy supply.
2. Biodiesel is carbon neutral because the balance between the amount of CO_2 emissions and the amount of CO_2 absorbed by the plants producing vegetable oil is equal.
3. Biodiesel can be used directly in compression ignition engines with no substantial modifications of the engine.
4. Blending of biodiesel with diesel fuel increases engine efficiency.
5. The higher flash point of biodiesel makes its storage safer.
6. Biodiesel is non-toxic.
7. Biodiesel degrades four times faster than diesel.
8. CO, CO_2 and UBHC, PAH, soot and aromatics emissions are reduced in biodiesel and its blends than in fossil diesel because biodiesel is oxygen in structure and it burns clearly all the fuels.
9. It is biodegradable.
Disadvantages of biodiesel
1. More expensive due to less production of vegetable oil.
2. Blends of biodiesel above 20% can cause engine maintenance problems and even sometimes damage the engine in the long term.

create a biodiesel blend or can be used in its pure form. It can be used in compression ignition engines with very little or no engine modifications because it has properties similar to mineral diesel (Banapurmath et al., 2008; Devanesan et al., 2007). Vegetable oils offer almost the same power output with slightly lower thermal efficiency when used in diesel engines (Makkar et al., 1997; Pramanik, 2003; Agarwal and Agarwal, 2007; Tiwari et al., 2007). However, Banapurmath et al. (2008) reported that compared to the fossil diesel operation, biodiesel from *Pongamia pinnata* (Honge oil), *J. curcas*, *Hevea brasiliensis* (rubber) and *Calophyllum inophyllum* resulted in poor performance associated with higher emissions, but on the whole it was seen that operation of the engine was smooth and existing engines could be operated with the biodiesel without any major modification. The advantages and disadvantages of using biodiesel are summarised in Table 7.

The fact that the oil of *J. curcas* cannot be used for nutritional purposes without detoxification makes its use as energy source for fuel production very attractive. *J. curcas* oil was used as a diesel fuel substitute during the Second World War in Madagascar, Cape Verde and Benin. Early engine tests with *J. curcas* oil were done in Thailand showing satisfactory engine performance. A 50 h continuous test and starting experiments were conducted using transesterified *J curcas* oil, No. 2 diesel fuel and their blends in two small pre-combustion-chamber – type diesel engine (Gubitz et al., 1999; Recep et al., 2000).

Conclusions

J. curcas L. is a multipurpose species with many attributes and considerable potential. The plant is traditionally used for medicinal purposes, but is also useful for the prevention and control of soil erosion, as living fence, and is also a source of oil which can be con-verted into biodiesel. The plant is widely seen to have potential to help combat the greenhouse effect, create additional income for the rural poor, and provide a major source of renewable energy both locally and inter-nationally. The oil from its seeds is the most valuable product since it can be converted into biodiesel. Biodiesel has become more attractive as an alternative to fossil diesel because of its environmental benefits and the fact that it is made from renewable resources. *J. curcas* L. is a promising source of biodiesel since its seeds contain high amount of oil and the species has good agronomic traits. These properties of *J. curcas* L. have attracted a lot of projects developers. At present, many countries have started cultivating *Jatropha* trees on large scale, although little is known about the positive and negative effects of the large scale production of *J. curcas* L. on ecology as well as other socio-economic situations. There is need to research on the life cycle analysis (LCA) for the biodiesel production from *Jatropha curcas* L. at small scale and industrial production units particularly in developing countries where there is large scale production of *J. curcas* L. The LCA studies will result in data on the energy balance, the greenhouse gas balance and the land use impact (soil, water, vegetation structure and biodiversity) of the *J. curcas* L. biodiesel system. Moreover, there is still lack of scientific evidence to support claims related to *Jatropha* high oil yield production particularly at large scale. Other claims of low nutrient requirements, low water use, and low labour inputs are true in combination with high oil yield production. There is also a dearth of indisputable scientific information on its potential yield under sub-optimal and marginal conditions, causing difficulty in predicting yields in future plantations under sub-optimal conditions, the conditions where *Jatropha* is suppose to prove its value.

The technique to covert vegetable oil to biodiesel has been developed particularly for edible oils like rapeseed, soybean, sunflower, canola etc. Of the several methods available for producing biodiesel, transesterification of vegetable oils is currently the method of choice. The production of biodiesel by transesterification process employing alkali catalyst has been industrially accepted for its high conversion and reaction rates. There are few studies reported on transesterification of non-edible oil like that from *J. curcas*. *Jatropha* oil contains about 14% free fatty acid, which is far beyond the limit of 1% free fatty acid level that can be converted by transesterification using an alkaline catalyst. There is need to investigate an appropriate method for the transesterification (with regard to the appropriate catalyst and other variables that affect the transesterification process) of crude *J. curcas* oil based on its properties. Recently, enzymatic transesterification has attracted much attention for biodiesel production as it produces high purity product and enables easy separation from the by-product, glycerol.

This biotechnological approach is environmentally friendly as well since the unrecovered enzyme can degrade naturally in the environment and also because of the mild conditions under which it is operated. But the cost of enzyme remains a barrier for its industrial implementation and many efforts are being carried out to improve the cost effectiveness of the process. The fuel properties of *Jatropha* biodiesel are comparable to those of fossil diesel and conform to the American and European standards. A diesel engine can perform satisfactorily on biodiesel blends without any major engine hardware modifications.

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