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Biofuels for Defence Use: Past, Present and Future

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ABSTRACT

Defence sector desires to attain energy self-sufficiency and security. In recent years, emergence of biofuel as an alternative source has raised the hopes of Defence. Ethanol and bio-diesel are currently being used as blends in different parts of the world. While, bio-diesel is mostly being blended in 2-20 per cent in different parts of the world, ethanol blending has reached upto 85 per cent. Owing to the sustainability reasons, the choice of feedstock for ethanol production is gradually changing from corn to lignocelluloses biomass. *Jatropha curcas,* is still the choice feedstock for bio-diesel in most third world countries. This institute has put in rigrous efforts to identify high yielding varieties of Jatropha, improving its yield, standardising trans-esterification to obtain high quality bio-diesel and its trials and testing in various vehicles and equipment. Second generation biofuels using biomass such as farm and forest wastes as feedstocks are promising in terms of their overall sustainability and volume produced. They can be used as drop in fuels. However, time is required to utilise their potential fully. Algae, the third generation biofuel feedstock still needs extensive R&D to make it economically sustainable. Whatever, the technology used, defence forces will accept any biofuel, which should be available constantly and priced below the existing petroleum fuels. The scope of producing by-products and finding a lucarative market for these products can ensure that prices of biofuels remain lower than the petroleum fuels.

Keywords: Algae; Bio-diesel; Biofuels; Biomass; Defence; Ethanol

1. INTRODUCTION

The petroleum based liquid fuels are widely used in the transportation, industries, agriculture, and defence sectors. The increased use of petroleum based fuel is associated with environmental concerns such as increase of CO_2 level in the atmosphere causing greenhouse gas effect, emission of sulphur, polyaromatics, particulate matters**.** Defence sector is traditionally an intensive user of petroleum-based fuels to meet their transportation and related needs. Most countries like USA, China, India, Russia, etc.; with large armed forces, meet their fuel demands by import of crude oil from oil and petroleum exporting countries (OPEC). Consequently, researcher world over are focussed on deriving alternate and sustainable fuel in order to have self-reliance on energy.

Biofuels, as the name suggest, originate from a biological feedstock by microbial, chemical, biochemical or thermochemical processes as shown in Fig. 1. At present, ethanol, bio-diesel (fatty acid methyl esters) and green diesel (hydrocarbons) have required properties to be used as biofuels, and are being produced and used at different scales in different parts of the world. The enthusiasm for biofuels all over the world is because of four major reasons. First, biofuels provide option to reduce dependency on fossil fuels without having to significantly change the way we use our fuels currently.

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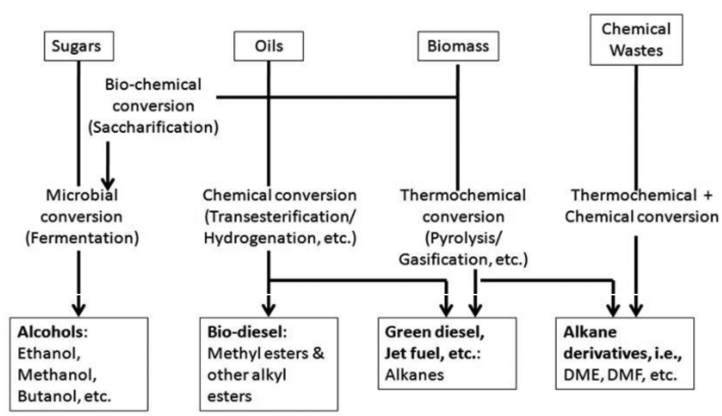

Figure 1. A schematic diagram showing varieties of feedstock, processes and biofuel end products available at present.

Second, biofuels can ensure energy security especially to emerging economies, and especially for defence sector. Third, it is perceived that use of biofuels would have environmental benefits, and fourth avenues for employment generation open up[1]. However, it is generally agreed that to meet these targets, multiple approaches will have to be taken up simultaneously[2] as shown in Fig. 2. For example, in US, six process strategies namely cellulosic ethanol, cellulosic green diesel, fast pyrolysis, hydropyrolysis, hydrothermal liquefaction and gasification[3] are simultaneously being pursued in order to derive biofuels from lignocellulosic biomass.

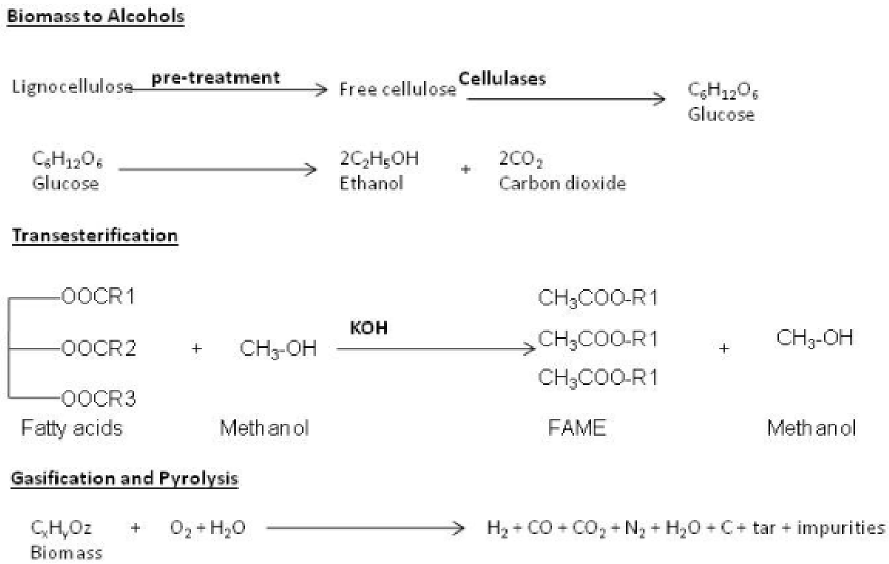

Figure 2. Some representative reactions depicting biofuel technologies and end products.

First generation biofuels, that is, ethanol and bio-diesel to a great extent relied on carbohydrate rich and oilseed crops respectively. However, the availability of these crops is limited, and requires the diversion of resources required for cultivating food towards the farming for fuel, which is unethical[4]. Therefore, alternative feedstocks, which are abundantly available, are being looked at and technologies for conversion of these feedstock to fuels are being developed. For example, waste cooking oil (WCO) or used cooking oil (UCO) is rapidly becoming choice feedstock for production of bio-diesel despite poorer conversion efficiency to bio-diesel[5,6]. This is because there is a 74 per cent lesser environmental impact of WCO to bio-diesel process than that of Jatropha oil to bio-diesel[5]. Biomass including agricultural residues and wood are also promising feedstock for producing a variety of biofuels like ethanol, methanol, butanol, green diesel via biomass to liquid (BtL) processes and even bio-hydrogen[6,7]. Biomass by itself can replace oil and coal for heating and energy production with adequate emission controls. Biomass is abundantly available as wood and other forms on earth. Estimates suggest that out of 350 billion m^3 of wood is available on earth[8], 3 dry metric ton (t/ha) per year of woody biomass is available, which corresponds to 13.5 million kcal/ha. The net energy input to output ratio is estimated to be 1:25[9]. However, biomass in its direct form is limited to domestic or related applications, whereas the liquid biofuels derived from the lignocellulosic biomass are alternate to conventional petroleum based fuels.

Fuels from biomass can be used to run vehicles, furnaces, boilers, gensets, cooking stoves and fuel cells. For such purposes, definition of biomass is expanded to organic urban wastes and leftovers, and also residues from industrial processing and agricultural fields. Dedicated biomass crops like switchgrass and miscanthus are rich in cellulose also constitute important feedstock for liquid fuels[10]. Still many experts believe that biomass production at present is not such rapid process that it caters for the entire replacement of fossil fuels[4].

There is a strategic importance of using biofuels by armed forces round the world. First of all, the consumption of fuel in military is growing, not only for transportation and power generation, but also to sustain variety of complicated gadgets and defence electronics which are energy intensive devices. Second, fuel convoys are easy targets of enemy forces and terrorists. Even if these convoys are not attacked, they are often tracked to detect the location of the Army. Most biofuels can be produced and utilised locally. This eliminates the vulnerability of detection of Army posts by enemy. They also become less susceptible to physical or cyber sabotage. As biofuels can not only ensure operating vehicles and gensets of military, but can also power supersonic jets[11], utility of biofuels in military are on rapid rise. Certain biofuels, for example the microbial fuel cells are easier to generate, store and distribute power, thereby increasing portability and manoeuvrability of the forces. Further, fuel cells do not produce heat, therefore they go out of the range of the detection by Infra-Red (IR) cameras.

Realising the potential of biofuels for defence research, agencies like DARPA in USA and DRDO in India have invested in their R&D. Here, we undertake a comparison of various biofuels for their suitability and shortcomings with regards to their possible use in Defence sector.

2. USE OF BIOFUELS IN HISTORY

Biomass is the earliest known fuel for mankind. Ancient civilisations heavily relied on firewood as source of energy. In many parts of the world, firewood, charcoal derived out of it and dried cakes of cow dung are still being used for fulfilling total/partial energy requirements for domestic use. Research interests in recent history had been focussed for the use of biofuel as alternate to conventional petroleum fuels. The patent literature reveals that first US patent on use of alcohol as a fuel was awarded in 1834[12]. Rudolf Diesel invented the compression-ignition (CI) engines in 1900 where vegetable oil was used as fuel[13], later on, the availability of middle distillate fuel replaced the vegetable oil. Nikolaus August Otto ran his early car engines in 1860s on ethanol. Early cars from Herny Ford too ran on absolute ethanol.

Business interests, however, reversed with discovery of petroleum reserves in early 20th century. Diesel gradually started replacing vegetable oils, and petrol started replacing ethanol. With elevation of taxes on ethanol, it was reduced to be an anti-knocking additive in combustion engines from being the primary fuel[14]. Till the end of World War II, ethanol-petrol blends ranging from 15-45 per cent were being used in different countries[12,15]. Even, vegetable oils were being used as emergency fuels during World War II. It is well documented that Japanese battleship Yamato ran on refined soybean oil[13].

The Fischer-Tropsch process was developed in Germany during the World War II to derive liquid transportation fuel from coal. Even after WWII, during the periods of petroleum crises, use of biofuels had been used as an alternate fuel. However, economies tend to reverse back to be 'petroleum-based', as the prices of crude oil fall. This trend kept continuing till date.

At present, the technologies for production of ethanol and bio-diesel are mature and these are produced commercially in industrial scales to be used as blends. The drop-in biofuels like green diesel, bio-butanol, etc. are the advanced fuels where the technologies for their production are at various stages of development. Each one of these is associated with several advantages and limitations. Overall sustainability of these fuels must be evaluated and compared as shown in Table 1.

Table 1 Analysis of sustainability of biofuels

Criteria	Ethanol	Bio-diesel	Cellulosic ethanol	Green diesel	Algal fuels
Cost of production[16, 17]	High	High	High	High	High
Economic development of farmers/society[9,18]	High	High	High	High	High
Employment generation[19]	High	High	High	High	High
Energy balance[3,20,17,21,22]	Low	High	High	Low	High
Land and water resource utilisation & competition[2,17,20,23,24]	High	Lower	Low	Low	Low
Emissions[3,17, 20,24,25,26]	Lower	Low	Lower	High	Lower
Impact on biodiversity[23,27,28,29]	Negative	Positive	Neutral	Neutral	Positive

3. BIOFUEL CROPS

These days the focus of the world is shifting towards Biofuel crops or bioenergy crops or Energy crops, which can and would be grown primarily for production of biofuels. Because cellulosic biomass is primary product from these crops, these are also called cellulosic crops or biomass crops. The idea of purpose-grown biofuel crops to a great extent help meet the Intergovernmental Panel on Climate Change (IPCC) expectations of bioenergy with carbon capture and storage (BECCS)[30].

At present, most of cellulose is derived from agricultural residues of crops like maize, sugarcane and sorghum. Presently, the biomass yields from maize is 4-7 Mg/ha[31]. However, diversion of these yields to fuel production, instead of their recycling to enrich soil nutrients reduces the fertility of the soil, requiring more application of fertilisers[32]. Compared to maize, sorghum produces more biomass, at the expense of lesser nitrogen fertiliser. Dry biomass production for sweet sorghum and photo-period sensitive sorghum can be as high as 32 Mg/ha, while forage sorghum yields upto 24 Mg/ha[33]. Interestingly, the genetic base of Sorghum is wide, making it amenable to be developed as bioenergy crop[34].

Non edible cellulose yielding crops like miscanthus, switchgrass, sweet sorghum etc. are likely to become hot BECCS candidates in near future. It is predicted that these energy crops would yield more biofuel than the currently popular agricultural residues by the year 2030[35,36]. Contrary to these annual crops, current opinion on bioenergy crops are those which are perennial in nature. These crops would incur less annual input cost and would be able to recycle nutrients. Additionally, these crops have better solar energy conversion efficiency. Their reduced environmental footprint owes to the fact that their roots dig deeper in the soil thereby binding it, which then leads to less water runoff and soil erosion. Therefore, they can grow on marginal lands[37]. Miscanthus (*Miscanthus* × *giganteus*) is considered well suited to the temperate regions United States and Europe[10], with yield potential of as much as 41 Mg/ha[37,38,39] between three to five year. Switchgrass (*Panicum virgatum* L.) is another promising bioenergy crop with yield potentials of upto 19 Mg/ha[35,37-40].

Tree species with short life cycle like poplar and Salix willow too are likely BECCS crop candidates, and are grouped in this category as Short Rotation Woody Crops (SRWC)[30,41]. Salix willow has shown a yield potential of 27.5 Mg/ha[42]. American Sycamore (*Platanus occidentalis*) has shown a yield potential of 23.3 Mg/ha[43]. Poplar has a higher yield potential of upto 55 Mg/ha[39].

Land requirements for BECCS crops, however, are substantial and therefore raise questions on their sustainability in terms of their competition with food crops. To eliminate the competition with the food, additional acreages are required, which would be available on deforestation. Thus, substantial carbon enrichment of the environment occurs and this also reduces water availability as well as causes loss of habitat to wild species. Clearing of Amazon forests to meet ethanol demand in Brazil is a case-in-arm example.

4. PRESENT DAY BIOFUELS: ETHANOL AND BIO-DIESEL

4.1 Ethanol

Biofuel production worldwide is dominated by ethanol from various feedstocks like corn, sugarcane, etc. Ethanol is one of the economically viable biofuel, and associated with its own disadvantages in terms of sustainability. The indirect land-use effects, food crops as feedstocks has created a food vs fuel situation, which has raised the concerns for ethanol as fuel for future[44]. Nevertheless, nearly 40 per cent SOx emissions are reduced on use of 85 per cent blend of ethanol (E85)[1].

Recent advances in internal combustion engines (ICE) coupled with prevailing low petroleum prices, and the extensive infrastructure worldwide for refining petrol and utilising it makes it difficult to be challenged by ethanol at present. The net energy gain for ethanol production is also not favorable. For every 1 gallon of oil used in production, only about 1.3 gallon ethanol is produced[17]. Air quality index too is not much improved, as greenhouse gases are emitted both in cultivation of the feedstock as well as production of ethanol. Nitrogen use efficiency (NUE) of corn, the primary source of ethanol is poor, and thus tons of Nitrogen fertiliser is washed away during irrigation, causing huge water pollution[11].

Nevertheless, Defence as well as civil sector is open to ethanol, and as a result most countries have started shifting to cellulosic ethanol. Ethanol can prove to be a replacement for petrol in light duty fleet. While ethanol derived from food sources may not be sustainable in long run, and the one from cellulose can be attractive if the by-products too be the 'sought after' materials. Biomass crops like switchgrass may be useful as these are efficient nitrogen utilisers, store carbon reduce greenhouse gases[17].

4.2 Bio-diesel

Bio-diesel is alternative to diesel fuel derived from vegetable oils, and is thus obviously used in diesel engines. Diesel engines are attractive for their energy efficiency, but suffer with the disadvantage of being more polluting in nature. Use of bio-diesel to a great extent improves emission characteristics without significantly compromising their efficiency.

The primary feedstock used in Europe is rapeseed, though other food crops like canola, sunflower, soybean, etc. too have been used bio-diesel feedstocks[45]. The vegetable oil is chemically modified by transesterification in order to reduce the viscosity by one-tenth with improvement in the volatility and other fuel qualities. The patent literature reveals that a Belgian patent was awarded in 1937 for the process of transesterification to obtain methyl and ethyl esters of vegetable oil (bio-diesel)[46,47]. Bio-diesel resembles to petro-diesel in terms of physical qualities. The qualities of bio-diesel is dependent upon the feedstocks used[48], leading to variations in the engine performances. *Jatropha curcas*, being projected by most third world countries as a biofuel crop, results bio-diesel of high quality for CI engines, suitable for use in different vehicle and machinery engines. However, low yield in jatropha is a serious constraint for full-scale exploitation of the plant for biofuels use. It is widely known that use of Plant bio-regulators can significantly enhance floral development[49].

This Institute has identified high yielding Jatropha varieties, and established agrotechnology in different agroclimatic zones of the country. Inter-cropping with vegetable, fodder and biofuel annual crops has been practised to enhance the economic returns from Jatropha fields. This institute has also standardised an alkali catalysed transesterification process in a 1000 liter per day processing plant, and optimised to obtain bio-diesel meeting IS 15607:2016 specifications. The Jatropha based bio-diesel have been extensively used for trials and testing by Indian Army and Navy for their vehicles (2.5 Ton and 4.5 Ton vehicles) and equipment (13, 112 and 160 kW diesel generator sets) under various conditions like plains, plateau, highways, city roads, sea shore and desert. It has been observed that use of bio-diesel blend B20 can reduce CO emissions by 15 per cent. The unburnt hydrocarbon, which is mainly polyaromatic hydrocarbons (PAHs), is also reduced to 50 per cent. Bio-diesel being an oxygenated fuel and free from polyaromatics, helps the diesel to burn completely leaving less hydrocarbons in the exhaust. The 4 per cent increase in the NOx emissions by the use of bio-diesel may be due to the presence of esters with straight chain C_{16}-C_{22} structure where combustion occurs at high temperature peak zone, causing oxidation of atmospheric nitrogen. Feedstock for bio-diesel is free from sulfur and expected to reduce the SOx emission when blended with diesel fuel.

4.2.1 Economic Issues Related to Bio-diesel

Prices of bio-diesel in successive years fluctuate, as nearly majority of the cost of bio-diesel stems from the cost of the feedstock, which in turn depends on the agronomic inputs to the crop. In Indian context, where biofuel crop *Jatropha curcas* is grown on lands unsuitable for food crops, the yield and the cost of seed depends on the rains in the Monsoon season. The cost of bio-diesel may become competitive when feedstock prices become favourable after a good rainy season. However, cost of conventional diesel also varies in successive year, yet it remains the benchmark for the cost of bio-diesel. Undoubtedly, farming for bio-diesel in marginal lands can turn out to be profitable venture if all the by-products attain good market value, even if the main product that is the bio-diesel is sold at a price comparable to the conventional diesel**.** As per estimates, a 5 per cent of the cost fluctuations can end up bio-diesel being costlier or cheaper than the petro diesel[47]. Apparently, feedstock prices will keep varying every year. Nevertheless, only a minor fraction (2-20 %, varies from country to country) of bio-diesel will be blended with normal diesel.

5. BIOFUELS IN DEVELOPMENT PHASES

5.1 Cellulosic Ethanol

Acid hydrolysis of wood can yield fuel grade ethanol and furfural. Ethanol derived from wood and grasses is commonly called as cellulosic ethanol. Based on the life cycle assessments, the combined climate change and health cost of cellulosic ethanol is about four times lesser to gasoline. All the grasses as well as crop residues rich in cellulose can be converted to ethanol. The delignification would require environmentally hazardous processes like acidification, thermal treatment, microwave, etc.

5.2 Green Diesel

Lignocelluloses can also be converted to fuel by pyrolysis (Fig. 3), gasification and gasification coupled with Fischer-Tropsch process (Fig. 4), catalytic upgradation (Fig. 5) and other methods. Pyrolysis involves combustion of biomass in absence of oxygen, the end product being bio-oil. The 'bio-oil' or 'bio-crude' find application in furnaces, boilers, etc. The minor products are charcoal and gases. The non-condensable combustible gases are formed to lesser extent, which can be captured and used. Bio-oil can be fractionated and upgraded to useful fuel, the technology is in research and development stage.

Gasification is similar to pyrolysis, except that it is performed at a higher temperature and lesser pressure. The output of gasification is a mixture of gases, collectively called as 'producer gas'. A pure mixture of CO and H_2 obtained from similar process is called syngas or synthetic gas, which is having high calorific value. Syngas can be used to power boilers, run gensets, and even to operate combustion ignition engines. Syngas can further be converted to a mixture of hydrocarbons including Green Diesel by Fischer-Tropsch

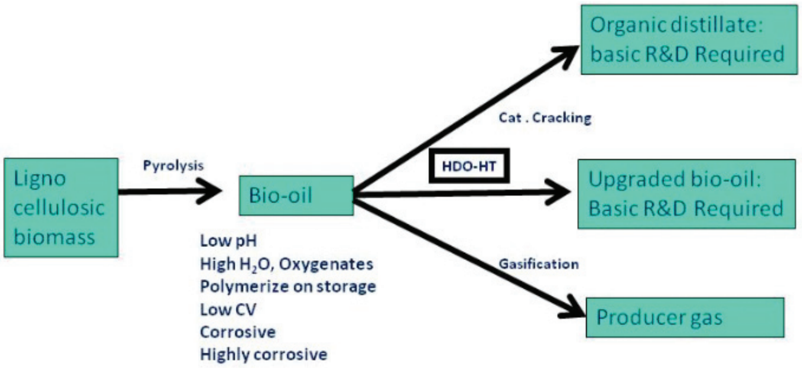

Figure 3. Summary of pyrolysis reaction and possible end products.

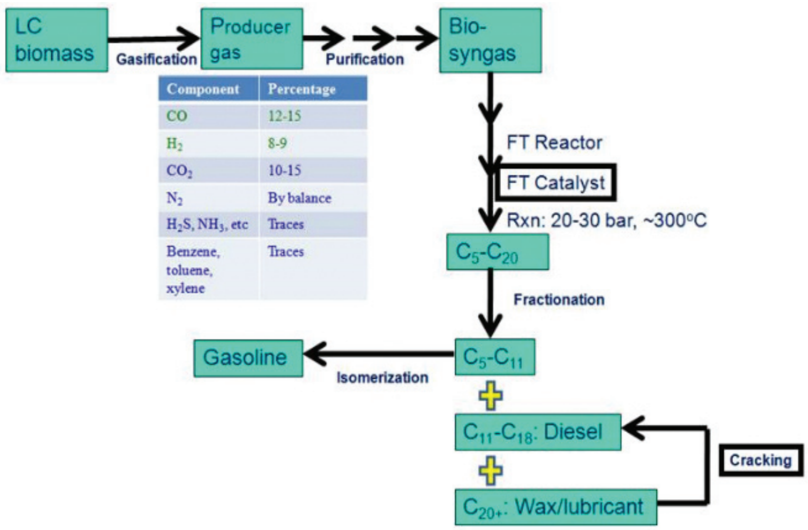

Figure 4. A schematic diagram showing flow of events in gasification and Fischer-Tropsch reaction.

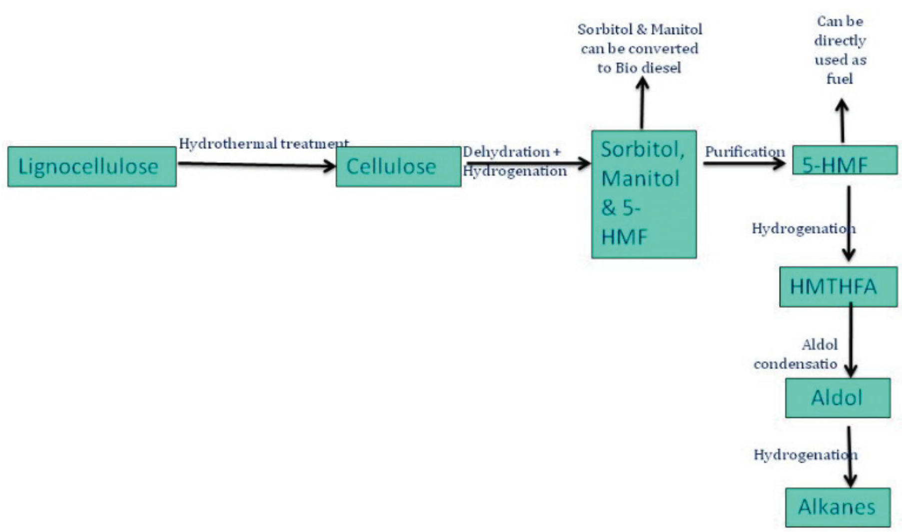

Figure 5. A schematic diagram showing catalytic pathway of conversion of lignocellulose to hydrocarbons. Here, 5-HMF stands for 5-Hydroxymethylfurfural, and HMTHFA stands for 5-Hydroxymethyl-tetrahydrofurfural.

(FT) process, which is yet to see commercial exploitation, and technology is in development stages only.

British Airways shelved the BTL project due to lack of government support[50,51]. There are ongoing projects by Air Liquid and CEA, Fulcrum Bio-energy Inc. to build commercial BTL plant. As an emerging technology, very less information is available for fully integrated system of gasification, biomass cleaning and FT synthesis as most commercial processes are kept confidential for the obvious commercial interests. Further, there are difficulties in operation due to multiple interactions between integrated processing steps.

Nevertheless, green diesel is free from sulphur and polyaromatics. Once commercialised, it will be readily adopted by Defence as well as Civil sectors since it is chemically similar to conventional diesel.

5.3 Other biofuels

Bio-butanol is in industrial phase in USA with companies like Butamax Advanced Biofuels LLC and Butyl Fuel LLC pursuing its production enthusiastically. Production of bio-butanol is a microbial process achieved by *Clostridium acetobutylicum* and *Bacillus butylicus*. Many other countries like China, UK, France and Austria too are betting upon bio-butanol as a fuel of future and are scaling up its production[14]. Use of butanol can reduce 32-48 per cent GHG emissions[52]**.**

Methanol and Dimethyl ether (DME) are other biofuels which can be produced from biomass as one of the by-products in gasification and further synthesis[20]. Many countries including India are considering these fuels to be a promising alternative of diesel in future. Theoretically, 35-40 per cent yield of methanol from biomass can be obtained[53]. DME is derived further from methanol. Use of bio-DME in vehicles has substantial advantages in cutting off the pollutants from the air compared to the fossil fuels. Upto 60 per cent SOx are reduced by the use of bio-DME in vehicles[1].

All these three biofuels described above can be stored at pressure similar to LPG, and being simpler low molecular weight, short side-chained oxygenated molecules, burn clearly. Their use requires moderate modifications in the diesel engine.

6. ALGAE- THE THIRD GENERATION BIOFUEL

The earliest known initiatives on Algal biofuel R&D dates back to 1978, when the US Department of Energy's (DOE) aimed to produce transportation fuels from algae. Algae, which collectively refers to microalgae, macroalgae and cyanobacteria, convert solar energy to chemical energy through photosynthesis, and can be grown in heterotrophic conditions with an exogenous source of organic carbon. They can be harvested on a daily basis, and oil productivity from algae easily exceeds that of oil crops[55]. Interestingly, algae have a potential of yielding as much as 80 per cent oil by weight of total cell mass. These theoretical claims forecast the possibility of up to 3,00,000 l/ha/year of oil per year[20]. However, the actual yields from algae did not emerge anywhere closer to that figure. In fact, the actual yields turned out to be only a fraction of these projections. Most commercial ventures in USA including that of Solazyme, Algenol and PetroSun have failed leading to closure of most ventures.

Interestingly, US DOE's programme on algal biofuels was terminated in 1996, as the contemporary cost of fuels being derived from algae was between 3-6 time that of the petroleum fuel[2]. Market realities have failed to match theoretical claims on potential of algae so far, and cost of oil from algae is still more than 50 time the claim[20]. In recent years, petroleum oil prices have been volatile, and concerns over mitigating carbon excess in environment have also grown. Some estimates indicate costs of algal oil and algal fuels are falling comparable to petroleum fuels now[56]. Consequently, algae as source of biofuel are being revisited, for the tremendous capability of absorbing carbon from the environment. It is possible to grow algae in industrial effluent and areas rich in CO_2 emissions. The current business challenges are scalability and costs involved[2]. Technically, harvesting and drying before extraction of oil or biomass remains a challenge for developing algal fuels. Besides that, algae shade one another's cells leading to different levels of light saturation in the cultures. As a result, there are different rates of growth of algae. Wild strains and bacterial infections can also invade open pond cultures, leading to fall in oil production from algae.

7. FUTURE TRENDS

There is no doubt that biofuels will have an important role in meeting energy needs of defence sector in future. However, the biofuels that would be in use and the way these would be used would be different from what we see and perceive today. Bio-diesel and ethanol are technically feasible and proven biofuels of the present days. However, they both suffer with a number of disadvantages. Use of higher blends of ethanol, in particular has direct and indirect undesired impacts on ozone layer[23]. Infact, ethanol and bio-diesel are currently being used only as blend and not as pure fuels. Current geo-political conditions too are driving the world away from the use of first generation ethanol and bio-diesel.

Green diesel and bio-butanol are likely alternatives, which do not suffer with present generation of biofuels. In Europe, Switchgrass and miscanthus are being seen as promising feedstocks[10] with half the land requirement to that of maize and one third the water requirement compared to maize for producing equal amount of ethanol[57]. A well planned biofuel development strategy with diversified agricultural cropping systems including perennial grasses like switchgrass and miscanthus can have long lasting beneficial effects on environment and energy security[10]. It is possible to grow food, fuel, fodder from the same field with careful planning. Such multifunctional agricultural systems have positive impact on biodiversity as well[27].

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