Sustainable Biofuels for Electricity generation in Sudan

ABDELNASIR OMRAN

MSc by Research

ASTON UNIVERSITY

June 2017

Aston University

Sustainable Biofuels for Electricity generation in Sudan

Abdelnasir Omran

MSc by Research

2017

Thesis abstract

Sudan was separated into two countries in July 2011. Before this Sudan was the most significant country in Africa with a total area of around one million square miles. Due to the separation, Sudan lost about 75% of the fossil fuels resources and currently facing a very severe economic crisis. As a result of this, the government had to abolish the fossil fuels subsidies which used to cost about 15% of the total expenditure of the country.

Only about 30% peoples connected to grid electricity. Sourcing fossil fuels alternatives are crucial to meet the growing energy demand, political stability, and growth of the country. This study aims to investigate the feasibility of using locally available renewable biofuels for small-scale electricity generation and implementation in Sudan. A combined qualitative and quantitative methodological approach was used to study the potential of seed based small or community-scale energy production in Sudan to resolve the severe fuel shortage after secession. Estimation of various types of available biofuels was carried out. There is around two million ton of Jatropha biofuel that will be available in 2019; around four thousands ton of cottonseed biofuel and two thousands ton of castor biofuels available annually. In this investigation, 23 types of neat biofuels and blends were prepared using ethanol, butanol, and fossil diesel. Physicochemical properties of all neat biofuels and blends were measured and compared with standard fossil diesel.

Heating values of Jatropha, Cottonseed, and Castor biofuels were 39.18, 39.74 and 37.71 MJ/Kg respectively. Neat biofuels and blends were tested in an unmodified 2-cylinder diesel engine. Engine performance and emission characteristics were conducted and compared with standard fossil diesel results. Jatropha, Cottonseed, Castor biofuels were blended separately with 20% butanol and 20% fossil diesel. The neat biofuels and blends were tested successfully in a 7.4 kW indirect injection two-cylinder engine. Jatropha biofuel and its blends showed 7% higher brake thermal efficiency than fossil diesel at maximum load. For Cottonseed biofuel and its blends, Castor biofuel and its blends were 6.7%, 8% higher, respectively. Jatropha biofuel blends with 20% fossil diesel and neat Jatropha oil showed 53%, and 18% high CO and CO_2, respectively; while both samples showed a smoke reduction of 96%.

NO_X emission for neat Jatropha and its blends showed a decrease in the range 5 – 13%. Cottonseed oil and its blends showed NO_X emission decrease in the range 5 – 7%. Castor oil blends have demonstrated the highest NO_X emission reduction among all tested samples with 24%. Smoke production reduction of Cottonseed oil and its blends were in the range 62 – 91%. Castor oil blends with 20% butanol showed 24% NO_X emission reduction, while its blends with 20% fossil diesel showed 10% reduction. Both samples of Castor oil blends showed smoke production cuts; blends with 20% butanol showed a decrease in the range 59 – 62%, while blends with 20% fossil diesel showed 61% reduction.

The study concludes by this short-term engine testing that this Compression Ignition engine type can be efficiently operated with 20% butanol blend with any of the three non-edible biofuels, Jatropha, Cottonseed and Castor, without any modification. Sudan has the potential of increasing the production of biofuels from these three plant and butanol can be produced locally to minimise the cost of fossil diesel import. The reduction of NO_X emission and smoke production could help Sudan reach its Green House Gas reduction target.

Keywords: Biofuel, Sudan, engine, electricity, combustion, emission.

" ظَهَرَ ٱلۡفَسَادُ فِي ٱلۡبَرِّ وَٱلۡبَحۡرِ بِمَا كَسَبَتۡ أَيۡدِي ٱلنَّاسِ لِيُذِيقَهُم بَعۡضَ ٱلَّذِي عَمِلُواْ لَعَلَّهُمۡ يَرۡجِعُونَ"

Corruption has appeared throughout the land and sea by [reason of] what the hands of people have earned so He may let them taste part of [the consequence of] what they have done that perhaps they will return [to righteousness][1].

[Glorious Quran (Ar-Rum (85)]

This thesis is dedicated to:

My Mother;

My Father;

My family

Acknowledgments

ALL PRAISES ARE DUE TO ALLAH, THE LORD OF THE UNIVERSE, THE MOST MERCIFUL AND THE MOST GRACIOUS.

I am grateful to my supervisor Dr. Abul Kalam Hossain for sharing knowledge and experience with me; for his patience and his endless support. I would also like to express my deepest appreciation to my associate supervisor Dr. Philip Davies for all his support during my time at Aston University. I am grateful as well to my teacher Mr. David Smith for all his technical advice and for the teaching opportunity which he honoured me with to enhance my teaching skills. I would like to thank Dr. Lilly Jeanette and her team for their help and support as well as Dr. Thomson Gareth, the head of our department and all his staff for facilitating this study.

I am thankful to Mr. Refahtalab Pedram (a final year Mechanical Engineering student, who was my trainee during test rig preparation and engine testing) for his perseverance and support. My gratitude also to Mr. Masera Kemal (a Ph.D. student) and Mr. Ahmad Ako (Aston University postgraduate) for their help and support during our engine testing.

Finally, I would like to express my great appreciation to Mr. Ali Mohammed, Dr. Mohammed Khalid, Dr. Mojab, Dr. Husam Ibrahim and Mr. Salam Omar (from our Sudanese community in Birmingham) for their help and support.

Table of Contents

Nomenclature

70CO30BT	70% Castor biofuel plus 30% Butanol
80 CO20ET	80% Castor biofuel plus 20% Ethanol
80CO20BT	80% Castor biofuel plus 20% Butanol
80CS20ET	80% Cottonseed biofuel plus 20% Ethanol
80CS20BT	80% Cottonseed biofuel plus 20% Butanol
80CS20FD	80% Cottonseed biofuel plus 20% Fossil Diesel
80JA20BT	80% Jatropha Curcas biofuel plus 20% Butanol
80JA20FD	80% Jatropha Curcas biofuel plus 20% Fossil Diesel
80PO20FD	80% Peanut biofuel plus 20% Fossil Diesel
90CO10BT	90% Castor biofuel plus 10% Butanol
90CO10ET	90% Castor biofuel plus 10% Ethanol
90CS10BT	90% Cottonseed biofuel plus 10% Butanol
90CS10ET	90% Cottonseed biofuel plus 10% Ethanol
90JA10BT	90% Jatropha Curcas biofuel plus 10% Butanol
BT100	Butanol - 100%
CO100	Castor biofuel - 100%
CS100	Cottonseed biofuel - 100%
ET100	Ethanol – 100%
FD100	Fossil Diesel – 100%
JA100	Jatropha Curcas biofuel – 100%
PO100	Peanut biofuel – 100%
SE100	Sesame biofuel – 100%

Figures

Tables

Chapter 1: Sudan Energy Background

1.1 Sudan Energy Background

The total area of Sudan (officially known as The Republic of Sudan) after secession is 1,861,484 sq km[2]. In 2015, the population was 40,235 million inhabitants with a growth rate of 1.78%[3][2]. The capital city, Khartoum, alone inhabited by around 10 million. Sudan neighbours (from north anticlockwise): Egypt, Libya, Chad, Central Republic of Africa, South Sudan, Ethiopia, Eretria and the Red Sea.

Separation left Sudan and South Sudan in a very severe economic crisis. Sudan had to change its fuel subsidies which used to cost the government around 15% of the total expenditure[4]. Sudan used to meet its energy need through renewable, in particular, the utilization of biomass; and evidence showed that renewable is gaining ground, again, after the separation shock. It is also worth noting that the agricultural division is getting back attention, more detail can be found in subsection 1.3.4.3 Agriculture.

Regarding political stability, Sudan government was arguing that the peace agreement with South Sudan will be reflected in the economy and socio-political stability but in contrast, soon after the signing of the peace agreements in Naivasha in Kenya, another war deepened in the north-western Darfur region.

The war started in 2003, by small attacks from Darfur rebels, Justice and Equality Movement (Jem) and The Sudan Liberation Army (SLA). These rebels accused the Central government of injustice and lack of equality in dealing with Darfur and Darfur's tribes; however, some experts suggested that there was the tension of land for many years between Arabs nomadic and Fur's farmer[5].

Whatever the reason for war was, the government tried to control it by force, and that escalated the situation and led to a crisis in the region; reports announced that thousands of lives lost and millions displaced. Since then the situation is revolving in a circle of war and peace agreements.

Some of the more significant findings to emerge from this subsection is that Sudan after 2011 is facing an enormous economic and socio-politics crisis and energy shortages. These results suggest that, in general, looking for oil alternatives is crucial for stability in all sectors.

Aston University

Illustration removed for copyright restrictions

Figure 1: Sudan’s map (2014) [2].

1.2 Fossil Fuels and Electricity generation in Sudan

1.2. 1Introduction

Over the past century, globally, there has been a dramatic increase in fossil fuels exploration, production, and consumption. The investigation actions commenced in Sudan in the 1960s. The focus was on the coastal water of the Red Sea and the Sudanese mainland shelf, but it was detected, 18 years later, in the border with South Sudan; in block one, two and four[6].

A Recent study[4] indicates that these blocks have the most oil and gas reserve of both countries. According to Oil & Gas Journal (OGL), South Sudan and Sudan had 3.5 and 1.5 billion barrels proven oil reserve, respectively. This study shows that both countries are not producing or consuming natural gas. Nevertheless, it was confirmed that there are around 85 billion cubic meter reserves, gas expansion had been limited; it is whether flared or reinjected to improve oil production level[4].

Regarding electricity, the past years have seen increasingly rapid advances in the field of power, but millions of people are still without access to electricity.

1.2.2 Oil and Gas

The quick increase in oil exploration, production, and refining in the period 1995 – 2011 could have lit the prospects of Sudan economy as general and the energy sector in particular by depending totally on fossil fuels revenues. Before the secession, in 2010, Sudan become the second largest oil producers in Africa, outside the Organization of the Petroleum Exporting Countries (OPEC)[4].

According to oil and gas journal, the production of oil in Sudan reached 414,000 b/d in 2006, with plans to increase it to one million b/d by 2008[7]. In 2010 around 0.6 % of the global oil production came from Sudan. In 2006, Sudan became the sixth largest oil producer in Africa[7].

Aston University

Illustration removed for copyright restrictions

Figure 2: Consumption of Sudan's oil products [8].

Apparently, oil was one of the major players the secession of Sudan. This withdrawal left Sudan with enormous investment in oil-related facilities but modest production share. That was shocking to Sudan’s economy. Sudan lost 55% of its financial proceeds and about two-thirds of its external exchange incomes. The export revenues become only $1.8 billion in 2012, compared to $11 billion in 2010. The oil used to be 60% of the total administration incomes in 2010, and it dropped to 27% in 2012. In Figure 3, it is apparent that Sudan’s oil production has dropped significantly in 2012[4].

Figure 3: Sudan's and South Sudan's oil production [4].

In contrast, South Sudan possessed 75% of the oil production share with no refining or exporting infrastructures. Moreover, the remaining 25% is on the border between the two countries, and it was subject to regular disruptions since then, due to the conflicts that pursued the separation. Figure 5 and *Table* 1 illustrates the oil production blocks and infrastructure in Sudan and South Sudan. The most remarkable infrastructure is the 850 miles pipelines with the capacity of 500,000 bbl/d. These lines have numbers of heating system alongside it to aid the flow of the waxy crude petroleum[4].

Regarding fuel management, apart from Sudan’s and South Sudan’s national fossil fuels companies, Asian national fossil fuels companies dominate the fossil fuels sectors in both countries. Table 2 shows the names and countries of all the companies operating in Sudan and South Sudan.

Table 1: Oil production blocks and operators in Sudan & South Sudan [4].

Table 2: Major petroleum companies in Sudan and South Sudan [4].

There are numbers of complicated borders and fossil fuels related issues which still need resolving. These problems escalated the situation and led to a new war. Under pressure from the African Union and the U.S. and China, they signed a deal to share the fossil fuels revenues[2]. Despite the agreement, the production of both countries never reached the position of the first-largest non-OPEC African fossil fuels producer which was obtained before secession. In 2013, both together ranked as fourth. Figure 4 Shows the export figures of both countries in 2013[4].

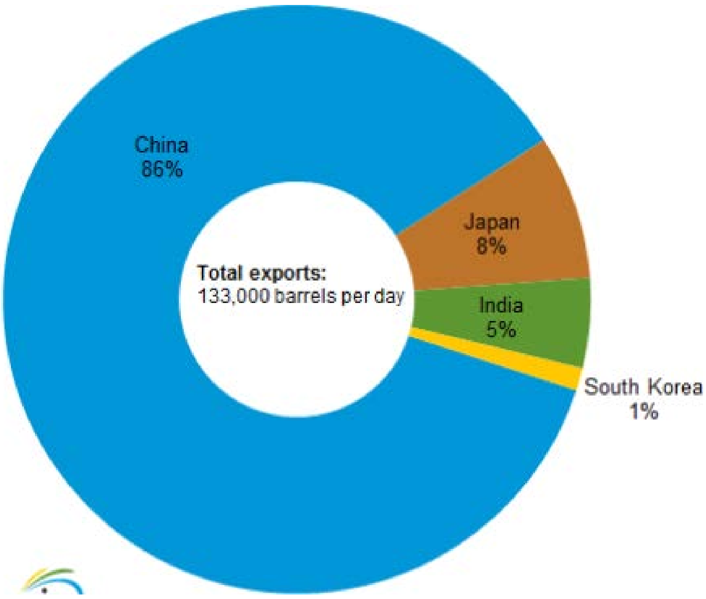


Figure 4: Crude petroleum export of Sudan& South Sudan[4].

As far us Natural gas concerned, it has never been producing despite the evidenced reserves of around 85 billion cubic meter. It was whether burned or reinjected into wells to increase fossil fuels yield. According to the National Oceanic and Atmospheric Administration (NOAA), Sudan before 2011 flared around 334 million cubic meters. That is equivalent to 0.2 % of the entire natural gas burned universally[4].

Aston University

Illustration removed for copyright restrictions

Figure 5: Sudan's & South Sudan's essential oil & Gas infrastructure [4].

1.2.3 Electricity generation

Since the founding of power, the usage is increasing rapidly in line with new technologies. It made life more convenient to the extent that life without it is unthinkable.

Experience shows that there is severe shortage electricity generation in Sudan in 2016. There are millions of Sudanese without power, nonetheless that the generation has more than triplicated within the last 16 years. The International Energy Agency reported, in 2011, that 71% of Sudanese did not have access to electricity. In 2012, generation was 9.7 billion kilowatt-hours (kWh) which covered South Sudan consumptions as well; 68% of the production was hydroelectricity, 27% diesel and heavy fossil fuels and 5% of biomass and waste as it illustrated in figure 6[4].

Aston University

Illustration removed for copyright restrictions

Figure 6: Sudan's electricity generation by fuel[8]

1.2.4 Conclusions

The exploration actions to discover fossil fuels and gas in Sudan commenced in the 1960s. In 1978, petroleum and gas explored in the border with South Sudan. This discovery together with other reasons spoiled the peace agreement with South Sudan and led to the secession of the country. The exploration of petroleum and gas could have, but the unified Sudan in an adamant economic position but the separation brought both countries back to tensions, conflict, and war; petroleum and gas become a curse more than a gift.

Nevertheless, electricity from diesel and heavy fuels were only 27%, Sudan is facing severe shortages in generation due to the loss of fossil fuels revenues.

All in all, Sudan was forced to look back for renewable energy as an alternative to fulfill the gap between generation and demand.

1.3 The Wind and Solar Energy in Sudan

1.3.1 Introduction

Experience shows that Sudan profoundly depends on fossil fuels, biomass, and hydropower to fulfill the energy demand to the grid-connected areas; nonetheless, researchers were forced to start looking for an alternative due to climate change, depletion of fossil fuels, and high energy demand.

According to the International Energy Agency, the global production of renewable energy stretched to 1,894 Mtoe in 2014. That stretching denotes about 1/7 (13.8%) of the entire Primary Energy Supply (TPES) of 13,700 Mtoe[9]. Figure 7 illustrates the share of renewable energy globally. The most remarkable fuels in the renewable domain are biofuels; it is the most implemented kind of fuel, and it matured in line with total TPES of 2.5%.

Figure 7: The global total primary energy supply division by fuel share [9].

Aston University

Illustration removed for copyright restrictions

1.3.2 Wind energy

1.3.2.1 Introduction

Wind power is one of the renewables and clean energy which can be implemented using two systems; the first system consisted of a sail and vertically fixed shaft; a prominent example of this is the traditional sail boats. This kind was known in China and Japan as early as 2000 B.C. The other system is the horizontal axis wind turbine, which has been in operation in the Netherlands and the United Kingdom since it was invented in the 12th century. It was mainly used for two purposes: corn grinding and water pumping in order; to safeguard existing lands from flooding and reclaim that land. Due to many reasons, the advancement of wind turbines appears to have paused for around six decades. Some studies suggested that; the main reasons were the development of the Internal Combustion Engine and the expansion of fossil fuels production[10]. The horizontal axis wind turbine forms one of the pillars of renewable energy resources.

1.3.2.2 The Prospects and Challenges

Prospects:

To find the viability of using wind energy in Sudan, Omar[10] examined 70 wind anemometers around the country and produced an annual wind speed map. Figure 8 presents the breakdown of wind speed and the name of some major cities in Sudan.

Figure 8: Sudan wind speed map(m/s) [10].

He concluded that wind power would be suitable for limited areas and minor projects. A recent study[11] shows that at an altitude of 50 m, in contrast with 10m of the previous survey, potential wind speed in all areas between 4.0 to 7.0 m/s. Figure 9 provides an overview of wind speed at 50 meters height in all African countries.

Aston University

Illustration removed for copyright restrictions

Figure 9. Wind speed map of Africa. Source [11].

From a technical viewpoint, the annual wind speed map, which Omar[10] developed shows that around 50% of Sudan has a yearly average wind speed above 4 m/s; in this study, he identified the north part of Sudan as a more suitable area for the development of wind power. It surpass 5 m/s in the Red Sea cost. The Red Sea state is suffering from a shortage of drink water. Wind turbine power could be used for water desalination stations. In an earlier study, Omar[12] suggested this area for wind power generation while recommended the North part of Sudan for water pumping due to the suitability of wind speed, close to surface underground water and social and political stability in that region.

However Sudan is known for its Wind energy potentials since the 1920s, but it seems as though that, it has never been utilized extensively. Apparently, many types of research have been paving the way towards utilization of wind power since the 1990s, which led to the start of some pilots wind pumps stations around the promising areas in North and East Sudan. Some of these wind pumps have been designed, developed and manufactured by the privet sector in Sudan[13]. According to a recent study[11], Sudan wind energy potential is as high as 90% of the total yearly power consumption. High wind energy potential, suggests that wind power can solve the deficit between production and consumption with minor cover from other renewable resources. A cording to a technical feasibility study Sudan is the second higher among sub-Saharan African countries regarding wind energy potential; with 20 and 10million tons of oil equivalent (Mtoe) at high and low altitudes respectively; figure 10 displays the results obtained by the study above. Since German turbine siting density is the most highly developed in 2005, it has been used as a standard for that study. High denote to the current force and low denote to 60% [11].

Aston University

Illustration removed for copyright restrictions

Figure 10. Onshore Wind energy potential in some African countries (Mtoe). Sources [11].

Challenges:

Despite the fact that Sudan has a gap in energy production, only 40% of the population has grid Electricity access[11], and the high potential of wind supply energy, utilization of wind power is deteriorating. On the other hand, Studies showed that neighbouring countries have several completed projects. Egypt in the lead with 550 MW followed by Kenya (5.1 MW) then Eritrea (8.0 MW). In Ethiopia, there are around three projects ongoing and planned[11]. Since the countries around Sudan were able to exploit wind energy, it is hard to explain why Sudan could not. Apparently, it has related complications, whether economic, social, political or environmental which could have stalled utilizing wind energy. It seems as though that wind power is not on the agenda yet.

The most studies in the field of wind energy in Sudan have only focused in water pumping; the Energy Research Institute in Sudan (ERI) managed to start a pilot project with 15 wind turbine from Holland (CWD 5000). The primary focus of the project is a water pumping around the capital city of Khartoum[14]. It seems as though that the decision to start utilizing wind power in a big scale is still have not been made.

Germany is an excellent example of stimulating the private sector; before 1991 there was the insignificant growth of wind power energy. During that year, a new law came into force, Electricity Feed Law (EFL). By 1998 the utilization of wind power reached 3,000 MW and still growing since then. The EFL concentrated in two points; access to the grid and satisfactory price[15]. These two points were good enough for the Germany privet sector to accelerate the development of the wind energy market. This example indicates a need to understand the obstacles that blocking the way towards large exploitation of wind energy in Sudan.

1.3.2.3 Conclusions

Sudan has a favorable wind speed, flat lands in the most areas, scattered population and shortages in energy supply. Studies show that using its wind power potential would be more profitable. Sudan utilization of wind power is insignificant in comparison with numerous neighboring countries. Engaging the privet sectors in developing wind energy market is essential, but the initial effort from the public sector is crucial. The legislation is a key factor as Germany example showed in the period (1991-2000). The response of Sudan to exploit its wind energy, as many studies suggested, is not entirely understood.

1.3.3 Solar energy in Sudan

1.3.3.1 Introduction

Solar energy is the radiant light and heat discharged by the sun, and it is crucial to all life on earth[16]. The sun is instrumental in understanding renewable energy as general and solar power in particular. The configuration of sun and its physical appearance define the nature of radiation energy in the space. Duffie et al. [17] presented the details about solar energy components such as the receivers, storages, and load.

Research into solar energy has a long history. This section will focus on two key aims. Firstly, reviewing the solar energy potential in Sudan. Secondly, offers some important insight into the execution of Solar energy; specifically, the use of photovoltaic (Solar PV) and solar thermal energy (Solar TH). The PV & TH are known as an active exploitation of solar energy, in which the solar energy whether stored or converted for other utilizations. In contrast, the passive solar energy is related to building construction and design to maximize the use of sunlight and heat[18], but this is beyond the scope of this study.

1.3.3.2 Solar energy potential

It is now well established from a variety of studies that solar energy is the most abundant energy globally[19][20][21][22]. Figure 11 illustrates the reserve of conventional, and the annual potential of renewable, energies. It shows that the solar energy is larger than all other energy reserves. The global energy use was 16 TW-year in 2015; solar energy potential is 23,000 TW-year[20]. It has been conclusively shown that solar energy could, alone, surpass the global demand for years to come.

Figure 11: Renewable and conventional energy comparison (TW/year) [20].

Sudan is central in this discussion; data from several studies suggested that Sudan has an ideal position for harvesting solar energy[23][22][24]. An empirical study[23] compared the reading of 16 stations around Sudan, which measure the solar waves on a horizontal surface, with results from mechanical methods. (Table 3) shows the names and the monthly reading obtained from those stations within around seven years.

The previous study concluded that the reading and predicted figures were consistent. It suggested that the average global waves in the range from 3.05 to 7.62 ($kWh/m^2/day$). Figure 12 displays the Annual mean global sun signals map over Sudan. This result was supported by a recent study[22] which stated that most unindustrialized countries have an excellent position for ideal access to solar waves; looking to the solar resources map (figure 13), Sudan is located in the area with peak access to the cosmic waves. It is in the region where the average annual solar energy is ranged from 6 to 7.5 ($kWh/m^2/day$).

All in all, Sudan has ideal average solar waves which could be an excellent resource for heat and power.

Illustration removed for copyright restrictions

Table 3 : Station for measuring global sun waves on a horizontal surface [23].

Figure 12: Annual mean global sun waves over Sudan (MJ/m^2/day) [23].

Aston University

Illustration removed for copyright restrictions

Figure 13: Solar resources map [25].

1.3.3.3 Execution of Solar energy

Within three decades (1983-2013) solar power implementation has improved comprehensively[22]. The primary drivers for that were: 1) the energy crisis in 1973 which shocked the developed countries and as a result, it raises the awareness of looking for alternatives. 2) The high energy demands which put pressure on fossil fuels due to the change that industrialization brought to the way of life. 3) Climate change due to emission related to excessive consumption of fossil fuels. Data from several studies suggest that the future of Solar Energy promises[22][21][18]. Solar energy harvested in Sudan in small scale; mainly for power and heat using solar PV and solar TH respectively.

Solar PV:

In 1839, Becquerel was researching light's effect on electrolytic cells when he discovered PV[26]. More than a century later, Solar PV panels were developed at Bell Labs in the U.S. in 1954; the most popular usage has been in space satellites for power generation ever since the late 1950s[27].

Solar PV components are solid-state semiconductor apparatuses that transform rays into direct-current power. Different constituents used on PV plates: cadmium telluride, copper indium selenide, mono-crystalline silicon, polycrystalline silicon and microcrystalline silicon[26].

More details were discussed in a recent study[21]. Figure 14 shows the worldwide market production shares of Solar PV in 2011.

Aston University

Illustration removed for copyright restrictions

Figure 14: Manufacturers of PV cell in 2011 by production in MW [21].

Due to the fossil fuels crisis in 1973, there was considerable attention to developing it together with other renewable energy resources but soon when the fossil fuels prices dropped, market shrunken; this indicates that policies at that time were not motivated by environment sustainable strategy backing[28]. Fortunately, it has recovered as early as 2000, showing incredible growth recently[18]. From 2004 -2014, around 139 GW, as figure 15 presents, was the installing capacity of solar PV globally[29]; although the most installation was in developed countries as the report mentioned; Africa is a promising market.

Research, design, construction, and test of Solar PV in Sudan goes back to 1973 when the Energy Research Institute (ERI) built small solar stills with surface area in the range 1-4 m^2. According to ERI, these PVs could be used for different purposes such as water pumping, power and storage batteries charging. The design included portable and fixed PVs stills[24]

Aston University

Illustration removed for copyright restrictions

Figure 15: The global solar PV installation, 2004-2013 [29].

A study that covered Solar PV installation in Africa shows that Sudan entire facility in the year 2000, was less than 1000 and the estimated total PV capacity installed was 100 KWp[30]. In the same year, another study recommended that Solar PV for energy is a good option for water pumping whether for irrigation or drinking water, but it confirms previous findings and contributes additional evidence that suggests unaccustomedness with the technology is the reason for not been used widely[31]. In addition to that, the same study indicated that lack of sufficient solar waves measurement stations was a key factor which holding Solar PV technology from large expansion. To overcome this barrier, a recent study[32] proposed a set of equations for predicting the global sun waves through Sudan.

Seven years later, the use of solar energy, as a result of several studies, the consumption of solar energy using Solar PV has enlarged expressively. Mainly to provide electricity for homes in remote areas[33] and water pumping; this is an indication that, the measurements of solar radiation is crucial for engineering, designing and building Solar PV.

Recently, there was significant focus on Solar PV for water pumping. The emphasis can be illustrated briefly by a project funded by United Nations Development Programme (UNDP) with $4.8 m. It aims to replace 28 diesel-power with solar energy- power water pumps in North State[34] in the first phase. Figure 16 displays one of the replaced Solar PV which is in operations since 2014. The first phase will act us pilot project; to introduce and train farmers and others to the function, operation, and maintenance of Solar PV- powered water pumps.

Aston University

Illustration removed for copyright restrictions

Figure 16: Solar PV for water pumping installed in North State [34].

As a kind of stimulus for other participant's banks in the project; part of the $4.8m was deposited in a finance portfolio. This aim to inspire banks to fund the second phase which has an objective of installing 1422 units in the period 2015-2019.

Solar TH:

Solar Thermal is the seizure of solar energy to heat water or other liquids for different applications such as domestic hot water for heat and wash or industrial process heat. Another use of solar thermal is the conversion to mechanical energy. Solar Thermal has been an object of research since Archimedes time (287-212 B.C); nevertheless, his knowledge about the science of optics which empower him to invent a way to focus solar radiation on burning ship from a distance, was debatable his study contributed to existing knowledge of Solar Thermal. Athanasius Kircher (1601 – 1680) tried to validate Archimedes' finding[35]. However his study results were never found, but his work contributed to the historiographical debates concerning Solar Thermal.

Centuries later, a solar furnace has been made by the French chemist Lavoisier. He managed to construct lenses to concentrate sun waves, in around 1774. Figure 17 displays Lavoisier's solar furnace which consists of two mirrors with a 1.32m and 0.2m lens. This oven managed to achieve $1750°C$. Researches continues until it reached a breakpoint by the efforts in the 19^{th}

century to transform Solar Thermal to mechanical energy by using low-pressure steam to run steam engines[35].

Figure 17: Lavoisier Solar furnace [35].

In the present, many large Solar Thermal plants are operating around the globe. In 1979, the first marketable solar plant was set up in Albuquerque, New Mexico. It had the capacity to produce 35MW thermal from 220 heliostats. There are many solar plants around the globe generating superheated steam of 673K which is suitable for producing electricity or process heat for industrial[35].

The most traditional use of Solar Thermal today is the domestic water heat. The manufacturing started in the 1960s, and it developed rapidly. Figure 18 Shows roof-top solar collectors which feed a home with hot water; nonetheless, it should be connected to a boiler to top up heat water during another season apart from the summer[36]. Unfortunately, this technology has not been introduced widely in Sudan. A future study to implement it in Sudan would be fascinating.

As it was mentioned in (1.3.3.2 Solar energy potential), Sudan has a good position for utilizing solar energy. It has been reported that Sudan is well committed to adopting renewable energy, especially in remote areas.

Figure 18: Domestic water heating [36].

Solar Thermal can cover a range of industries and domestics need; such as Solar Thermal collectors which can heat water for many industrial processes, solar cookers and solar dryers for bricks, fruits, and vegetables. However, Solar Thermal systems are suitable for Sudan, but it has been neglected to compare with Solar PV[31]. Solar Thermal in Sudan worth investigation in future studies.

1.3.3.4 Conclusions

In this section, the aim was to give an overview of solar energy in Sudan, its potential, and utilization. The most obvious finding to emerge from this study is that Sudan has a high solar energy potential; the average global waves in the range from 3.05 to 7.62 (kWh/m^2/day). Regarding implementation, Sudan is still far behind its potential; the use of Solar PV and Solar TH are in small scales. Some studies show that there is some small scale project using Solar PV for water pumping and irrigations to replace the diesel-water pumps.

Overall this study strengthens the idea that more researches need to be done to introduce solar energy in Sudan in large scale to solve numerous problems related to energy shortages in Sudan.

1.3.4 Biomass and Bioenergy in Sudan

1.3.4.1 Introduction

Bioenergy denotes to energy resultant from the natural carbon fixation of plants or organic materials. Examples are biodiesel, resulting from plant biofuels and animal fats, and bioethanol, produced by the fermentation of biological compound of harvests like corn[37].

Biomass, in its simplest form, it is any materials that can be produced from plants and animals; such as; agricultural deposits, animal waste, woodfuel and charcoal It is a renewable organic matter which consists of carbon and a combination of biological molecules such as nitrogen, hydrogen, and oxygen[38].

Biomass can be separated into traditional and modern. The traditional biomass; such as wood-fuel, whether consumed as it is or altered to charcoal, animal slurry, and crop deposits, formed around 14% of the global energy consumption in 2001, mainly, in developing countries[39]. In 2012, it become 9% [29]. Figure 19 shows the reduction of traditional biomass utilization.

Modern biomass is the biomass that has been pre-treated and prepared from a range of biomass resources- comprising algae, energy crops, and organic waste[29]. In contrast with traditional biomass, it is mainly implemented in developed countries; that can be attributed to the availability of modern conversion technologies.

Figure 19: The share of biomass in the consumption of energy worldwide in 2012 [29].

Recent evidence suggested that traditional biomass is the primary fuels in Sudan. It formed 87% of the total Sudan energy consumption in 2005,[40]. *Table 4* shows the annual biomass volume sources available in Sudan.

Table 4: Annual Biomass volume sources in Sudan(10^6 m^3) [41].

1.3.4.2 Forestry resources & waste

The primary product for forestry is Wood fuel; this can be collected from forests or outside forest; examples of that are firewood and Stems. Other products of forestry are the deposits whether from forests such as stumps tops and branches; or wood business, and examples of that are sawdust, bark, and recycled wood[42]. All these products have been used for energy for centuries. Forestry waste is of interest because, in 2012, 85% of biomass used for energy worldwide originated from forests or trees[42]. Yield forest waste arises in the form of stumps, tops, and branches; while waste from wood industry comes in the form of bark, sawdust, other wood pieces, black liquor, tall oil, recycled wood and chips[42].

Nonetheless, Sudan had sufficiently of water, forestry and cultivated deposits resources, the excessive consumption of woodfuel (45%) and charcoal (30%)[40], for decades contributed, among other factors, to desertification, deforestation, and national resources degradation. A study, which has been conducted in 2000[43] shows that from the three million hectares of forestland in Sudan, about 9.5 million tons of oil equivalent(Mtoe) is the annual consumption.

Thus far, some studies have discovered the relationship between the utilization of biomass as general and wood-fuel in particular, and desertification and deforestation[44][41][39][45][43]. These resources have significant roles in the environment, health, social, economic and politics of developing countries and Sudan is not exceptional.

A Recent study suggested that wood fuel in Sudan, is bulky with a little heating value which results in high transport cost; and in addition to that, the widely used traditional cookstoves (Canun) and ovens have very low energy conversion efficiency[41]. To address these, and other energy related problems, Sudan went for two decades (1980-2000) through numerous programs; one of these programs, which was related to biomass, was improved cookstoves[44].

The open study has been designed to determine the implementation rate of these improved cookstoves and the factors affecting that. Nevertheless, that the improved, has and efficiency of (24.8%) which is higher by (7%) of the traditional, cookstoves; It concluded that the implementation rate was insignificant.

The study attributed that to the deficiency of thorough understanding of the Sudanese society and the characteristics of the distribution of labour and the supervisory process. It suggested, that although Sudan is patriarchal society, yet that does not justify, that the male is the sole administrator in all household matters and concerns. All in all the study indicating that females should be engaged in all stages of any studies regarding family issues; apparently, that was not the case of improved cookstoves study.

Table 5: Wood-fuel& Charcoal utilization in Sudan [41].

Aston University

Illustration removed for copyright restrictions

Another study[46] emphasized the role of the female in collecting and using biomass. The study suggested that female with the help of children are the primary wood-fuel collectors, especially in rural societies. As a result of excessive use, they forced to walk long distances and that compromise their time, health and safety. As a consequence, the female would not have enough time for the other jobs at homes. Moreover female are more exposed to smoke related diseases such as asthma and lung cancer due to woodfuels and charcoal firing.

One of the more significant findings to emerge from this sub-section is that the share of biomass in the consumption of energy in Sudan is very high. This large proportion contributed to deforestation, dissertation, resources degradation, health and socio-economic problems. An effort has been made to minimize the use of woodfuel by improved cookstoves, but a study shows that the use of it was minuscule. The transition to commercial energy could help reduce the use of traditional fuels or at least reduce it but unfortunately, a recent study shows that this development is petite in African and Sudan is not an exceptional[47]. biomass share in energy consumption was 76% in 2000 and it dropped to 51% in 2011[48]; this attributed to the increase of oil and hydro use as a source of energy in different sectors.

As a conclusion, 1) the way that wood fuel was implemented should be improved to minimize the consequences. 2) Introducing alternatives such as the new biomass to energy conversion technologies. In this case, wood fuel needs to be pretreated to convert it to gaseous, liquid or solid, fuels.

1.3.4.3 Agriculture resources & waste

Sudan has plentiful livestock and fertile lands. According to the World Bank, these two have a share of around 35-40% of gross domestic product (GDP); with larger investment and improved control, it could donate considerably more[49].

The report above from the World Bank, Showed that Sudan had recognized the crisis of its agriculture and livestock sector. This recognition mirrored in the Interim Poverty Reduction Strategy (I-PRSP) as well as the program for Economic Reforms which was acknowledged by the parliament in December 2014. This program will last for five-year. In contrast, a recent study[50] suggested that the agricultural division has always been neglected by the governments and the situation had been aggravated when all the consideration had been focused on oil and oil related industries. *Table 6* illustrates the stake of irrigated, rain-fed semi-mechanized and rain-fed traditional agriculture system in the agricultural sector GDP. The most remarkable decline was in the traditional rainfed system which fell from 24,6 % growth rate annually during the 90s to 2.4 %[51].

Table 6: Different agricultural scheme and its progression and stake of Agronomy GDP [51].

In the same period's harvests under irrigation were not performing as bad as rain-fed but in the same time it had not enhanced (

); the main reason was deprived administration. Once that problem solved there are high possibilities that the yields of sorghum, wheat, and cotton can be doubled while the yield of groundnuts can be raised by two-thirds[51]. According to FAO estimation, Sudan exported around 21 tons of cottonseed in 2013; with an export value of $24000. In comparison, Sudan imported 25 000 tons of castor beans oil in the same year with an import value of $66 000.

Aston University

Illustration removed for copyright restrictions

Figure 20: Sudan's castor oil seed production (1970-1998) [37].

Experience shows that Sudan was one of the major producer and exporter of cotton and castor beans in the 70s and 80s; castor beans was major corps in Al-Gash irrigation scheme in Al-SHARQIYA province (it is known today as Kassala region); The project administration based in Aroma city, 50 km north Kassala. Figure 20 shows the area harvested for castor oil seed between 1970 and 1998; it has never increased again.

Cotton and cottonseed had exceeded 50% of Sudan export income at that time[52], but due to the concentration shift towards oil investment and other reasons, it suffers together with other major corps.

Jatropha plant was introduced to Sudan in 2012[53]. Sudan started in 2015 to plant 42.000 ha to produce two million ton of biodiesel annually.

Aston University

Illustration removed for copyright restrictions

Figure 21: Farmers and On-farm Research Trials yields in the Gezira Irrigation Scheme [51].

Regarding Agriculture waste and by-product, it can be divided into three categories: woody and another form of by-products and herbaceous[42]. Herbaceous by-products include empty corn cobs, straw from cereals, corn, bagasse, rice, empty fruit bunch from oil palm[42]. According to Food and Agriculture Organization of the United Nations (FAO) agricultural and frost area were 108,678.80 and 19,907.60 thousand hectare, respectively in 2011[37].

Figure 21 shows that 71.1% of used land is permanent meadows and pasture. Which are real potentials for growing some non-edible oilseed plant such as Castro plant; this will affect neither its biodiversity nor its role uses carbon store, while it became a source of biofuels to solve some of the energy shortage in an environmentally sustainable way.

Figure 22: Sudan's land use in 2011[37].

For biomass, productive land is crucial. It is fundamental to Protect agriculture land against urbanization, degradation, and desertification [42]; the most of Sudan falls within the Sahara desert region with shoreline in the east closest to the Red Sea. That means high temperature and less rain in the north part, but the south part has a rainy season which could last between two and three months. Agriculture comes to pass along the Nile using pumps to irrigate crops such as cereal grains, sorghum, and millet. Vegetables and fruit are grown as well along the river. The most popular fruits are mangoes, Guava, grapefruit, paw paws, and oranges.

Among other crops; cotton, peanuts, sesame seed, molasses, and sugar cane can be classified as cash crops. Cotton has been grown in the El Gezira region (south the capital). This region is sparse prairie lying between the White and Blue Niles. It is one of the major irrigated zones in Africa[54]. Gum Arabic and dates palms were grown away from the El Gezira region. The first, developed in the West and the late in the north. These two crops are among the exports harvests. Sudan is the primary producer of gum Arabic[54].

Environmentally, Sudan divided to five different regions: flood region, montane vegetation, woodland savanna, semi-desert and desert[50].

The most significant factors which impact the irrigation, production system and livestock are the two Niles; the Blue and White Niles. The first flows from Ethiopia, and the late from Uganda, both confluences in Khartoum forming the River Nile which flows towards the Mediterranean Sea through Egypt (Figure 22). These two rivers have several seasonal rivers such as Atbara, Ad-Dindar, and Ar-Rahad. Other independent seasonal streams are Baraka, Al-Gash, and states; which have some of the major agricultural schemes around it. All of these are in Ash-Sharqiyah (Kassala) states.

As Table 7 shows, arable land is around 75% of total land in Sudan[50]; around two-third of it is uncultivated. From the small portion of cultivated land, production is still below expectation. However, the percentage of forest and woodland is higher than 40%, but a recent study showed that it is deteriorating year after year[43].

Aston University

Illustration removed for copyright restrictions

Figure 23: Sudan map before June 2011[50].

Table 7: Sudan's land use (1995) [50].

Nevertheless, the cultivated land is around 20%; it has been reported that large farming activities find a place; these activities can be categorized as follow: (1) Rain-fed, (2) Irrigation. These two could be mechanized or traditional. (3) Pastoralism/Livestock husbandry[50].

61 year before Independence Day, on first January 1956, Sudan economy main export crops was cotton (Used to be grown in El Gezira scheme). Cotton farmers were using rotating harvesting, with an unplanned extended period to circumvent the use of chemical fertilizers. In the 1970s that were altered by amplification and variation to increase output. Around 17 years later cotton production area was reduced and replaced with sorghum and wheat; some evidence suggested that there were two main reasons for that: firstly, attempting to have larger food self-reliance. Secondly, to solve the problem of water irrigation shortage; since sorghum and wheat require less water[50].

Aston University

Illustration removed for copyright restrictions

Figure 24: Seed cotton's area harvested (1969-2014) [37].

Traditionally, wheat used to grow in the North due to the suitability of environment and weather conditions. The scarcity of resident land and the high cost of irrigation required the government to encompass wheat crop growing not only to El Gezira Scheme but also to New Halfa Agricultural Production Scheme in ASH SHARQIYAH (figure 23); while, 75% of Sorghum grown in traditional and semi-mechanized rain-fed zones[50]. All in all, to date, there has been little convincing evidence that Sudan has reached high food self-sufficiently. It can be suggested that using the cotton seed to produce biofuels could bring cotton back as a major crop in El Gezira Agricultural Scheme; as figure 24 illustrate, the harvested area was around 527,000 ha in 1970, it dropped dramatically to only 65,600 ha in 2014[37]. Based on the calculation of All India Cottonseed Crushers' Association[55] biofuel in Sudan from Cottonseed can be estimated as follow:

$$Cottonseed\ of\ 65.600\ ha\ consist\ of\ \frac{2}{3}\ portion\ of\ seed\ cotton$$

$$65{,}600 * \frac{2}{3} = 43733.33ha$$

$$The\ world\ avarage\ per\ ha\ is\ 724kg\ of\ lint$$

$$43733.33 * 724 = 31663\ ton\ of\ oil's\ cottonseed$$

$$Each\ 8.32\ tons\ of\ cottonseeds\ produces\ one\ ton\ of\ oil$$

$$\frac{31663}{8.32} = 3805.65\ tons\ of\ oil$$

In the period 2000 – 05, agriculture was a low government priority due to the shift of investment towards oil. After secession and the loss of 75% of oil reserve, the focus turned back again to agriculture sector; nevertheless, this time the challenge is not only food security but energy problem as well. Fortunately, from arable land and water resources availability Sudan has the potential to become the first food and energy crops provider to the whole region.

From what was discussed earlier, it can be concluded that there is no biomass dedicated crops in Sudan apart from Jatropha curcas plant which was introduced to Sudan soils recently; nonetheless, the availability of arable land and water resources make that possible once there is a political well. Regarding waste, to date, all the waste have been used for direct combustion or build industry such as traditional homes, boats, and furniture. The globe annual energy demand is 400 EJ. Biomass energy conceivable from Forest, Agriculture, and animal waste are projected at about 30 EJ/year[56]. Sudan, if considered biomass as cash crops, could be one of the major exporters in addition to the fulfillment of the local energy demand.

1.3.4.4 Organic waste

Organic waste is a material that comes from plant and animal; such as municipal solid waste, food waste whether from industry or household. Biodegradability, which makes it suitable for energy production.

Municipal Solid Waste (MSW):

Municipal Solid Waste (MSW) is all the waste that generated in industry or household activities and managed by the local authorities. MSW consists of paper/cardboard, textile, glass, plastics, glass and food/garden residue. The diversity and quality of MSW depend on some elements: (1) residents earnings (2) The year's season and (3) generation point. Nevertheless, MSW is composing of many different components; organic waste is the high percentage. Figure 25 Shows the world's MSW arrangement[57]. Table 8 illustrate the breakdown of MSW from Sudanese cities; it indicates that 27% is vegetable, fruit and animal matter which is the most highly valuable waste for energy production.

Table 8: Breakdown of MSW from Sudanese cities (2005) [58]

Figure 25: World's MSW arrangement [57].

The generation of MSW in the world is increasing to an alarming number; according to an estimation by the World Bank, it will reach around 2.2 billion tons/year[57]. World Bank estimate created on trade and industry and population growth rate.

MSW in Sudan is one of the main impediments facing local authorities. A recent study shows that an individual in Sudan was found to generate around 0.6kg/day MSW[59]. Roughly, Sudan produces more than 8 million ton/year. The same study related the high rate of health and environment problem to poor MSW management. The study suggested proper MSW management and rigid observance to sustainable environmental rehearses would bring related diseases under control.

Figure 26: Constituents of MSW in Khartoum [59].

illustrates the MSW elements in Khartoum (the capital). Plastic form around 50% of features while organic waste is around 10%[59] in contrast with the global MSW production (figure 25). The previous study shows that MSW generation reaches 4000 tons/day in Khartoum and the surrounding area; which is 60.05 tons/month. This result indicates that Sudan is in the range of low-income countries. Table 9 shows the quantity of MSW generated in Khartoum state.

Table 9: MSW generated in Khartoum state [59].

Aston University

Illustration removed for copyright restrictions

Most of these MSW quantities dumped, spread or burned in residential areas as the previous study reported that 38% of MSW burned on-site (Figure 27).

Aston University

Illustration removed for copyright restrictions

Aston University

Illustration removed for copyright restrictions

Figure 27: (a)MSW dumped in Khartoum Market (b) MSW Dumped and burned in residential area [59].

Dumping and burning MSW in this way had a substantial impact on people health and environment[59]. An appropriate waste management system is a critical issue to take MSW to the stage of waste to energy conversion level using some of emerging thermal conversion technology such as Gasification and pyrolysis.

Food industry waste:

Newly, there has been new interest in using waste to generate energy. Waste can be classified to food, forestry and agricultural. According to Food and Agriculture Organization of the United Nations (FAO), food waste is the reduction of food in following phases of the food supply chain intended for human consumption[60]. It can be categorized as follow: (1) food waste from manufacturing such as dairy, sugar, breweries, fruit liquid industry and from butchery firms. (2) food waste from supplies, refectories, and residents[42].

Industrial Waste/Sewage sludge:

The industry sector is relatively small in Sudan, apart from petroleum related industries. The waste from these small industries is following the same route of MSW; whether dumped or burned in open areas around the major cities. The problem of these waste it is polluted, and it needs special waste collection management which is not available in Sudan. In the most cases, industries dump their polluted water into rivers especially the river Nile. Covert these waste to energy could be one of the ideas which inspire the adaptation of sustainable waste management and solving power shortages of small industries. A recent study showed that manufacturing subdivision is predominantly distressed from power shortages[61].

Sewage sludge is the core compacted leftover of the wastewater handling procedure; a recent study showed the sewage sludge derived intermediate pyrolysis oil is an excellent blend of biodiesel to run diesel engines[62]. In addition to that, experience revealed that sewage sludge could be used as biomass using gasification and anaerobic digestion technologies.

Sewage Sludge is abundant in Sudan, put it face management problem; there is no network for sewage sludge collection and treatment in the major cities. The disposal methods include collection in deep well and landfill. Both approaches have been polluting the soil and underground water for decades. Extracting energy from sewage sludge could solve this environmental problem in addition to the energy problem-solving.

Animal and Poultry wastes:

Animal and poultry wastes are among the most significant residues which are suitable for pyrolysis gas and liquid and biogas using pyrolysis and anaerobic digestion processes respectively. Sudan is rich with livestock production. The most common are cattle, camels, goats, sheep, and chickens. According to the World Bank, Crop growing and livestock donate roughly 35-40% of gross domestic product (GDP); with larger capital spending and enhanced authority, they could underwrite considerably extra[49]. *Table 11* illustrates the forestry, agricultural, water hyacinth and aquatic weeds wastes; as well as animal wastes which were around 1.1 million/m^3 of animal waste, annually in 2005. A recent study showed that there is 35 million head of cattle, sheep, and goats each; as well as three million head of camels, 600 thousands head of horse and donkeys and 200 thousand tons of food annually, consist of fish, wildlife, birds, and reptiles[58]. *Table 10* shows that Animal waste in 2005 was around 904,033 tons.

Table 10: Biomass supply per region of Sudan (2005) [58].

Table 11: Some of Annual available biomass in Sudan (2005) [58].

1.3.5 Biomass conversion technologies

1.3.5.1 Thermochemical conversion technologies

Thermochemical conversion of biomass is the production of energy by applying heat and using chemical processes.

Figure 28: Schematic of the different types of thermochemical conversion [63].

Combustion:

Combustion has long been a question of interest in a wide range of energy fields. The primary two types of combustion are solid or conventional fuels by direct burning or in and engine, respectively. Combustion is a principal contaminant of air, a major player in climate change and a primary source of lung cancer and further respiratory diseases.

Sudan has a long history of combusting wood, charcoal, and conventional fuels inefficiently as a source of energy. According to a recent study[64], Sudan is consuming around 13.8 million m^3 annually (*Table 12*). This combustion, remain over the past fifty years unprecedented; together with other facts, it brought Sudan to a severe deforestation and Sudan had to undergo a reforestation program of 1.05 million hectares[64].

Table 12: annual combustion of firewood and charcoal in Sudan (2002) [64].

Aston University

Illustration removed for copyright restrictions

Deforestation and depletion of energy resources and its consequences are important, but understudied, as the cause of concern. To address the issues of firewood and charcoal combustion efficacy, Sudan started briquette in 1980, focusing in agricultural residues. The first briquette machine was using groundnut shells and based in Khartoum. A 2 t/h was the second briquette machine which located in Kordofan state in western Sudan. This briquette has a maximum volume of 2000 tons per season. Not far from Kordofan state, in Nyala (Darfur state), a small scale briquette machine was working with a capacity of 0.5 t/h; it has 600 volume tons per season. The briquette plant was installed in central Sudan to deal with cotton stalks. It has the same capacity as the one in Kordofan. The last briquette plant is established in Eastern Sudan in New Halfa with a capacity of 1200 tons per season of bagasse briquette[64].

Pyrolysis:

Pyrolysis is the decomposition of biomass molecules by heat in the absence of oxygen using various type of reactors. A recent study suggested that the resulting oil from pyrolyzing biomass in an auger type intermediate pyrolysis reactor is a good blend to run IC engine. In this study, the oil was combined in different ratios with waste cooking oil and butanol. The study concluded, on the base of the small period of engine testing, that 30% of pyrolysis oil could be used in IC engine[65].

Pyrolysis has been used in Sudan to produce charcoal[64]. Looking to the variety of Sudan biomass, Pyrolysis could be a good option to be coupled to other thermal conversation technologies to produce liquid fuels.

Gasification:

Gasification is the production of carbon monoxide, hydrogen and carbon dioxide from biomass or other fossil fuel based carbonaceous materials. The process accrues in a reactor using high-temperature media such as steam-oxygen or air. The gas can be utilized in a gas engine to generate power[66].

Gasification in Sudan is still in its initial stage. In 2002, there was only three biomass gasifier in the whole country (*Table 15*).

1.3.5.2 Biochemical conversion technologies

Unlike thermochemical conversion, there is no extreme consumption of heat in biochemical conversion processes. In the composition of the biomass of lignin, cellulose, and hemicellulose; the process breaks down the hemicellulose to pave the way, to the reaction towards the cellulose[63].

Anaerobic digestion:

Anaerobic digestion is the production of methane by the itemization of biodegradable material such as food crop processing waste, animal manure, and sewage effluent, in the deficiency of oxygen[67]; figure 29 shows the process stages of methane production from biomass feedstocks. In the case of small domestic scale, as the case in India and China which is suitable for underdeveloped countries like Sudan, the process is much shorter, unlike the big commercial scale in the EU and other developed countries.

Figure 29: illustration of anaerobic digestion process [67].

Anaerobic digestion conversion process is the most accessible technology in Sudan. It was hosted in the mid-1970s when the first unit was built as a fragment of a plan for water hyacinth mechanism in central Sudan. In 2002, there were around 200 fitted units. These units cover a range of sizes; from small units which suitable for families in rural areas to medium and big scales which fit industries and great communities[64].

As recent study suggested, all the units have been made locally. The homemade units followed the design of the two most famous well-known types of digesters; fixed dome which was known as Chinese digester and floating gasholder which known as Indian digester. 120 units were built from the first, each with volumes 7 – 15 m^3 and 80 units from the later with sizes 5 – 10 m^3. For all big scale units, Cultivated and livestock wastes are the primary feedstock[64].

Fermentation:

Fermentation, in the main, is the disintegration of harvests which complemented by the development of gas. The most known one is alcoholic fermentation in which Sweetie is transformed into liquor and carbon dioxide. The total production of ethanol worldwide was 25.5 Mtoe, in 2007. It mainly produced in the US from corn and Brazil from sugarcane[67]. shows the production process of ethanol from both sugar feedstocks (sugarcane) and starch feedstocks (corn, cereals, and cassava)[67].

Aston University

Illustration removed for copyright restrictions

Figure 30: illustration of ethanol and co-products production [67].

In Sudan, due to the execution of the Islamic laws which was introduced in 1983, there are no alcohol distilleries. One of the reasons that Sudan has abundant sugar cane bagasse and sugarcane residues is that Sudan is the first sugar producer in Africa with more than five sugar factories in 2002 (Table 13).

Table 13: Biomass from sugar factories in Sudan [64].

Aston University

Illustration removed for copyright restrictions

The conditions for the implementation of the Islamic laws encouraged the privet sector to utilize the abundant sugar industries residues for energy generation. As an estimation, each of these sugar factories could produce 15 – 30 kWh per ton of cane[61]. As the previous study suggested, if all these factories have gasifier combined cycle systems, it will cover the entire Sudan's current electricity consumption by producing 400 – 800 kWh per ton of cane.

A recent study[68], which included ethanol production in Africa, suggested that Sudan is one of the wells suited for fuel-ethanol production due to the high production of sugarcane. The study estimated the production of molasses-ethanol in Sudan as high as 60 million litter per year.

Aston University

Illustration removed for copyright restrictions

Figure 31: KSC company owners [69].

Kenana Sugar Company is the largest sugar producer in Sudan and Africa; it was established in the 1970s in phases as a sugar company, and it has been enlarged for decades. It consists, today, of many sectors inclusive biofuel production. An ethanol plant commissioned in 2009; using the by-production, molasses, it produces high-grade ethanol – Anhydrous Alcohol (purity of 99.8%); the EU market is its largest single importer with 50%. Figure 31 illustrates the shareholder of the company[69].

The ethanol-Anhydrous Alcohol plant was built in consultation with a Brazilian's pioneer Ethanol's production equipment company (DEDINI). The total cost of building the plant was 35 million dollars. The capacity was 60 million liters per year in 2013. The company mentioned that by 2015, it would increase the production to 200 million liters per year; 50% of it will be exported, and the other half will be sold for the local market; the shareholders will inject 500 million dollars to fund the expansion. To facilitate the selling in the domestic market the company signed a deal in 2013 with Nile Petroleum Company, a Sudanese petroleum company, to sell it in petrol stations[70].

Transesterification:

Transesterification in organic chemistry has a wider definition; the one that related to this study is the process of producing biodiesel. In this case, it is the process of converting the fats or triglycerides, which is the main component of vegetable, humans or animals fat, to biodiesel using alcohol as an acid or base.

Aston University

Illustration removed for copyright restrictions

Figure 32: illustration of the process of biodiesel production [67].

The production of biodiesel from raw vegetable biofuels and fats to well established. The most used of vegetable neat biofuels to biodiesel include; soybean, palm, rapeseed, Jatropha, castor, cottonseed and peanut biofuels. Figure 32 demonstrates the process of biodiesel production from different biomass.

The process of biodiesel production in Sudan is still in it is an initial stage, nevertheless that Sudan is rich with vegetable and plant biofuels. Recently, Sudan started a project to produce biodiesel from Jatropha plant. The reason for choosing Jatropha plant is that there have been numeral examples of successful projects of high-quality biodiesel production from it is seeds and seedcake around the globe[42] [48][71][72] [73].

Jatropha curcas plant originally comes from Central America[48] and due to the similarity of whether it was adopted in many tropical countries such as India Nigeria and Sudan. It can cultivate in a different sort of raindrops schemes starting with 250 up to 1200mm annually. Depending on the rainfall, it could be planted in three separate way; 1) At an area of 2 meters by 2 meters 2) At an area of 2.5 meters by 2.5 meters, or 3) At an area of 3 meters by 3 meters. One of its useful advantages is that it grows in negligible lands with little nourishment content, but it necessitates soils that drain and ventilate well[74].

Table 14: Differences between Properties of Jatropha's oil fuels, Jatropha curcas biodiesel, and standard specification [48].

Aston University

Illustration removed for copyright restrictions

In addition to the advantages above of Jatropha curcas, Table *14* shows the physical and chemical properties of Jatropha oil in comparison with its biodiesel and the ASTM D 6751 and EN 14214 standards. The table shows that all the properties of Jatropha Methyl Esters (JME) is closer to the standards except flash point and water content which are higher than the norm by around 50% and 100% respectively[48].

All in all, besides Jatropha curcas, Sudan has another potential such as cottonseed oil, peanut oil, castor oil as first generation feedstock for transesterification and all the edible oil that was mentioned earlier as second generation feedstock by using oil factories residues.

1.3.6 Thesis Scope

1.3.6.1 Aims and objectives

Sudan has a very severe shortage of grid electricity which affect people lives and economy of the country.

The purpose of this study is to investigate the feasibility of using locally available biofuels for small and community scale electricity generation in Sudan.

The specific objectives of this study are:

- Review the energy and power overview of Sudan
- Assessing the types and quantity of potentially sustainable biofuels for electricity generation in Sudan.
- Preparation of test rig.
- Setting up and modifying the engine testing rig.
- Preparation of fuel blends and characterisation of its physical and chemical properties
- Engine performance and emission analysis using the available biofuels in Sudan
- Recommendations for sustainable biofuels to electricity generation in Sudan

1.3.6.2 Summary of chapters

This report comprises of seven main chapters, inclusive the background and introduction chapter. Below is a brief account of the other six chapters:

Chapter 2: In this chapter, the legislation and Economy of biofuels in Sudan were covered

Chapter 3: Chapter three covered the experimental setting and methodology.

Chapter 4: Chapter four was reserved for the literature review.

Chapter 5: Plant biofuels properties value and discussion were covered in chapter five.

Chapter 6: Chapter six covered Plant biofuels, engine performance and exhaust gas emission.

Chapter 7: In this last section, a conclusion and recommendations were given regarding energy potential and utilization in Sudan.

Chapter 2: Legislation & Economy of Biofuels in Sudan

2.1 Introduction

Sudan is rich with energy crops such as sorghum and millet, cotton, Castro plant, Neem, Cereal grains, vegetables and fruits, peanuts, sesame seed, Sugarcane, and molasses. Most of these corps are fit for human consumption except cotton and castor plant which has been used as export commodities as well as Neem which has been used as wood source and wind protection trees. Utilization of first generation biomass feedstock for biofuels would conflict with food crops; nevertheless, the most successful biofuels project in Sudan is using sugarcane and molasses to produce bioethanol.

Inedible plants such as Jatropha, castor, and cotton could solve the problem of food to fuel issues. These corps could be an option in a land where food crops are not economically beneficial due to dryness or poor irrigation system. In particular, Jatropha and castor could survive dry environments. In addition to biofuels, it could offer a new source of income for rural communities who live on or around marginal land[75].

2.2 Research and data availability

For decades researchers have been trying to pave the way towards renewable energy in general and biofuels in particular. Sudan has plenty of biomass option for biofuels production, but apparently, this sector is still in its initial phases of growth.

Since 1991, and after the establishment of the Ministry of Higher Education and Scientific Research (MHESR) planning was started to accelerate renewable energy development and implementation. The Ministry together with the Energy Research Institute (ERI) and the National Centre for Research (NCR) have been for years putting the base for broad of renewable technologies (*Table 15*)[64].

Table 15: Established renewable energy resources in Sudan [64].

Aston University

Illustration removed for copyright restrictions

Aston University

Illustration removed for copyright restrictions

Figure 33: Biomass consumption in Sudan (2000-2011) [48].

Figure 33 illustrates the use of biomass as an energy resource, but wood and charcoal which represent 83% were utilized in an inefficient way which created problem to the environment rather than been a renewable clean energy source (figure 34).

The most biomass that was mentioned earlier is an edible plant; diverting it from food to biofuels could intensify the food crises in Sudan.

Figure 34: Energy production by source [8].

To avoid any conflict with food the best option is to concentrate on the non-edible plant. Recently, there was a focus on Jatropha curcas plant to produce biodiesel.

2.3 Country legislation and strategy

Due to the secession of South Sudan, Sudan faced a big gap in energy production after losing, the primary energy resource, oil, and gas. Biofuels seemed to by the safe port. Unfortunately, there was no any comprehensive and advanced biofuels strategy comparing with many African centuries. A recent study, which investigated biofuels as an alternative to solve Sudan’s energy problem, announced the first Sudan’s National Roadmap for biofuels production[48]. According to the study; the Aeronautical Research Centre in Sudan originated the roadmap based on Jatropha’s oil as chief Feedstock and adopted the following points:

- Examine the funds related to the scaling up of biofuels production.
- All phases of progress have to be equipped with the latest expertise methods.

- Biofuels industry should be assured with an arrangement strategies and inducements in an exact timeline.
- Encourage collaboration and improve undertakings between all biofuels' industry stakeholder such as municipal, public and smallholders.
- Launching a Jatropha oil pilot plant in rural areas to decentralized energy production and stimulate the local economy.
- Implementing locally available biomass, perfectly as power generation resource.

2.4 Sustainable policy

Producing biofuels without intact the national resources of the country is a must not be a choice. Worldwide, is not acceptable, at least morally, to produce biofuels which regarded unsustainable; such as the use of food crops as biofuels biomass, generate more GHG to grow biomass for biofuels and using lands which have been used for food crops. Many countries are avoiding unsustainable development of biomass resources by using dense, agricultural and forest wastes. In addition to that, there is an increasing use of non-edible plant oil to produce biofuels and biodiesel[63].

In Sudan, there are two successful examples of sustainable production of biofuels; biodiesel from Jatropha plant which grows in less productive lands and bioethanol from sugar industry by-product. Fortunately, there are tens of vegetable oil which can be used for biofuels such as, cottonseed, Neem and castor plant.

2.5 Consequence on environment

Nevertheless, that biofuels improvement strategies have been obsessed by anxieties over energy retreat, the need for appropriate substitutions to conventional fuel, and an aspiration to decrease greenhouse gas discharges; Africa has a wider dimension for it. These aspects include the need to 1) uplift the burden of poverty, increase employments, and develop rural areas by improving the quality of life which in return minimize the internal migration to the major cities. 2) Solve the problem of electricity shortages in the countryside without increasing expenditure on conventional fuels. 3) Develop the biofuels production sector by improving the conversion technologies[76].

In 2002, CO_2 emissions per capita were 150 tons, which was not high, comparing to the world of 4.21 thousand tons. The most of it from the oil industry. One of the mitigation measures to decrease GHG is to reduce fossil fuels production and utilization[64].

A recent study[76] suggested that the way towards biofuels production could be costly to the environment. It suggested that in case of Africa; some question should be in mind to produce environmentally friendly biofuels; those issues include

1) Do biofuels production and processing has a positive impact on the environment?
2) Is it going to mitigate climate change and reduce greenhouse gas emissions?
3) Do it have an adverse impact on soils and water flows, cycle, biodiversity and habitat integrity?
4) How is it going to affect agricultural land and other land use alternatives?
5) Is the production of environmentally sustainable biofuels achievable in Africa?

2.6 Socio-economic impact

This point is related to the issue of sustainable production of biofuels. Since the most agricultural scheme in the rural areas, sustainable production of biofuels is suggested to benefit it the most. The rural areas are suffering due to the deprive situation of the agricultural sector. It is believed that biofuels production will create jobs, access to energy, attract capital investment and new technology. Sudan started the process of liberalizing and privatizing of some products which include energy sector since 2000. These policies released the government from some heavy burden of high prices of import products and encouraged the privet sector to invest in the energy sector[64]

2.7 Conclusions

In this chapter, the legislation and economy of biofuels in Sudan were covered. Regarding research and data availability, since 1991, and after the establishment of the Ministry of Higher Education and Scientific Research (MHESR) planning was started to accelerate renewable energy development and implementation. The Ministry together with the Energy Research Institute (ERI) and the National Centre for Research (NCR) have been for years putting the base for broad of renewable technologies. Although there was no any comprehensive and advanced biofuels strategy comparing with many African centuries; Sudan considered biofuels as an alternative. Due to the secession of South Sudan, Sudan faced a big gap in energy production after losing, the primary energy resource, oil, and gas; this gap force Sudan to come up with the first Sudan's National Roadmap for biofuels production. The road map covered all aspects of producing biofuels, such as sustainable policy, consequence on the environment and the socio-economic impact.

All in all, Sudan has taken all the necessary initial steps for huge investment in biofuels.

Chapter 3: Experimental settings & Methodology

3.1 Introduction

This chapter consists of two sections; 1) experimental setting. 2) methodology. The experimental section includes three main parts as well; (1) fuels preparation, (2) characterization apparatus and procedures (3) engine modification and testing procedure. Engine modification includes; Fuels line, Exhaust pipe and engine electrical circuit. The methodology section entail of (i) estimation of types and availability of various biofuels in Sudan. (ii) Preparation of fuel blends & Characterization. (iii) Engine Performance and Emission Testing and (iv) Recommendations on sustainable biofuels for Sudan.

3.2 Experimental settings

3.2.1 Fuels preparation

Jatropha oil was obtained from (Matrix Biofuels Ltd.) a UK supplier who imported it from Ghana. Cottonseed oil was purchased from (Mystic Moments UK). The oil extracted from the seeds of the cotton plant after the cotton lint has been removed. Castor oil was acquired from (Plantonic UK).

This study included 23 fuels samples, as figure 35 shows, from right to left: Fossil Diesel (FD), Cottonseed oil (CS100), Castor oil (CO100), Jatropha oil (JA100), Sesame oil (SE100) and Peanut oil (PO100).

Aston University

Illustration removed for copyright restrictions

Figure 35: FD, CS100, CO100, JA100, SE100 and PE100.

In addition to this, figure 36 and figure 37 shows the blends which were prepared from CS100 and CO100 with 10% and 20% of Ethanol (ET100) and Butanol (BT100).

Figure 36: CS100 and its blends with ET100 and BT100.

Figure 37: CO100 and its blends with ET100 and BT100.

The last eight samples blends which illustrated in figure 39 & figure 40 were, 90% of JA100 with 10% BT100, 80% JA100 with 20% BT100, 70% CO100 with 30% BT100, 80% CS100 with 20% FD100, 80% PO100 with 20% FD100 and 80% CO100 with 20% FD100.

Aston University

Illustration removed for copyright restrictions

Figure 38: BT100 blends with JA100 & CO100.

Aston University

Illustration removed for copyright restrictions

Figure 39: FD100 blends with JA100, CS100, PO100, and CO100.

The properties of some presented samples would not tolerate the use of pure plant biofuels in the engine, chiefly due to its low heating value and high viscosity. To find a way to improve the fuels value by blending; some plant biofuels were blended with 10% and 20% and 30% of Ethanol and Butanol. JA100, CS100, PO100, and CO100 were blending with 20% FD100 as figure 39 shows.

Regarding miscibility, the blends of CS100 with 20% of ET100 (80CS20ET) shows clear separation; while all other fuels did mix with ethanol and butanol. It was essential to shake it before any properties measurement. The reasoning behind why ET100 and CS100 are immiscible can be understood with explaining why water and oil do not mix. The molecules of water (polar) are more strongly attracted to one another than they are to the hydrophobic molecules of oil (non-polar) [77]. The oil molecules were excluded when water molecules bind to each other resulting in the oil molecules to cluster together[78]. Additionally, the difference in densities of the two liquids causes the two separate layers to form[77]. The liquid with the lower density forms the top coat. In this case, CS100 (920 kg/m3), has a lower density than water (1000 kg/m3) thus, forms a layer above the water. Ethanol has a density of 750 kg/m3 while CS100 has a density of 920 kg/m3. Therefore, ethanol forms a layer on top of the CS100 oil.

Ethanol molecules have both non-polar and polar parts. At low concentrations (mol/L), ethanol does not dissolve the oil so two separate layers could be seen. However, as the concentration (mol/L) increases, the ethanol starts to dissolve the oil and the two liquids mix.

Although there is around 60 million litre of bioethanol production in Sudan in 2013, production of biobutanol will require a miner modification to the existing process. As pervious study showed[79] biobutanol has many advantages over bioethanol:

- It can be blend with higher ratio with diesel.
- Easy to transport in existing pipelines since the blend with bioethanol has high miscibility with water.
- Biobutanol has higher Low Heating Value (LHV) of 27.8 MJ/kg comparing with 21.3 MJ/kg for bioethanol.
- Biobutanol has a high density and low vapour pressure which reflected on low level of volatile organic compounds during handling.

3.2.2 Fuels characterization

Properties of plant biofuels have been instrumental in our understanding of its suitability for testing in an engine to investigate whether it can be a good replacement for diesel. This section cover four subsections s; HHV, Density, Viscosity and flashpoint apparatus and measurement procedure.

3.2.2.1 High Heating Value

Heating value or calorific value is the amount of heat that released from fuel under test during combustion. This heat is the amount of energy per kg; it is a key factor in the competitiveness of fuels. In other words, when comparing two kinds of fuels; the HHV would show the energy contents per unit mass which in return would help in calculating the driving range of each fuel mass. Similarly, the price can be calculated per unit energy instead of per unit mass to get practical measure[80].

The HHV or the gross heat of burning of all samples is the heat of combustion includes the heat of vaporization of water, which occurs due to the oxidation of hydrogen. This water vapor condensed and cooled to reach the temperature of the bomb.

Concerning that, in the much real application, away from calorimeter, this water vapor is lost. As a result, the calculation of HHV seems to be not convincible, and this additional heat should be removed. By eliminating this heat, the term low heat value (LHV) is introduced. LHV is the net heat of combustion after removing the heat of vaporization of water. To do that the value of hydrogen must be known. If that the case then LHV can be calculated as follow:

LHV = HHV – (91.23) (H)

H = the weight percent hydrogen in sample

Despite all that, HHV remains popular because finding the amount of hydrogen in samples is a tedious job. This amount is reasonably low and often regarded as negligible[81].In case that the fuel test required to be compared with calculation, it is believed that there will be the slightly different result. The difference in result could be attributed to the operating conditions of Calorimeter. When the sample tested, the operating condition has to be reproduced. This reproducing would not be successful, all the time, as it should be due to human errors. Especially when the banana wires are connected, drops of water can be removed through fingers unconsciously. Because of those removals, the value of EE will change due to the modification of operating condition. Furthermore, in the calculation, no corrections were done for heats introduced by the fuse and acid formation while correction was done by the Calorimeter.

In addition to HHV, more can be obtained from the testing sample. The chemical reaction that occurs inside the bomb helps procedures to be developed to measure sulfur, halogens, and other elements. As it mentioned earlier, there is vaporization during the combustion. In the same time, the sulfur in the sample is oxidized to sulfur trioxide. This sulfur trioxide combined with that vapor and condenses as sulphuric acid [81].

The oxidization helped to build a procedure was developed to measure the value of sulfur and halogens and other different substances. These systems could be best described by showing the test of sulfur in fuels. In parallel with the analysis of HHV, the bomb can be washed, and Sulphate can be found in the water after some treatment, by adding barium chloride to form a barium sulfate precipitate. In the same way, many other substances can be found such as iodine, arsenic, and bromine.

To sum up, briefly, the calorimeter can be used to conduct various tests. In one hand, it shows the value of fuel under test, and on the contrary, it helps determine the gases, which affect environment and health.

Figure 40: Parr 6100 Calorimeter and Accessories (ASTM D420-90).

3.2.2.2 Viscosity

Viscosity is the thickness of the fluid, or in other words, it is the resistance to flow. That implies fluids with high viscosity are thicker than fluids with low viscosity. Viscosity decreases with temperature and increases with instauration. Among the disadvantages of high viscosity: poor spray characteristics and significant pressure drop in the injection pump. These two points lead to a poor atomization and incomplete combustion because of a big size fuel droplet into the chamber. This last point in the long term will result in wear and power loss.

To minimize the effects of high viscosity in biofuels, researchers have been using many technics; such as fuels preheating before injection, fuels blends with diesel or alcohols and dual tanks to start an engine with diesel then switch to biofuels to avoid cold start with biofuels.

Aston University

Illustration removed for copyright restrictions

Figure 41: Viscosity apparatus with hydrometer ASTM-D7544.

3.2.2.3 Density

The density of the fuel is its mass per unit volume.

Density = Mass/ Volume (kg/m^3)

Density can change due to change in temperature and pressure. All samples that were measured are liquids, which is incompressible. The pressure was neglected, but the temperature was measured. Measuring Density is essential for measuring the fuels volume ratio, which is important to measure, the fuel tank mass. The volume ratio is the mass ratio divided by Density. Density values changes due to change of fuels molecules weight. Moreover, it can change due to change of molecules weight of the components atoms of fuels molecules[80].

Aston University

Illustration removed for copyright restrictions

Figure 42: Density measurement using Hydrometer – ASTM D1298.

3.2.2.4 Flashpoint

Flashpoint is the temperature where fuel can instinctively burn. It is a safety measure. It shows the temperature that the fuel can withstands during storing before it became flammable. The high flash point the less concern.

Aston University

Illustration removed for copyright restrictions

Figure 43: 33000-0 SETA Flash Series 3 ASTM D3278.

3.2.3 Engine rig setting and procedure

Engine rig capacity is multifarious of equipment, arrangement and assistance service, contained in a structure modified or assembled for its drive. The primary purposes are to measure the power rating and performance; nevertheless, engine testing could be built for a specific task such as fabrication test, investigation of engine sound, lubrication or dissipate discharges[82].

As figure 44 illustrates, this engine rig consists of Lister-Petter LPWS2 – two cylinders, indirect injection, naturally aspirated water cooled diesel engine with serial number: 4300099LPWS2A0 02.

As

Aston University

Illustration removed for copyright restrictions

Table *16* shows, this engine set was built for fossil diesel only. Some modification was done before the conduction of biofuels testing; this amendment made it a dual fuels engine to compare the performance of both fossil diesel and biofuels. The modification was done on the engine. Nevertheless, the dynamometer was only lubricated and calibrated. This calibration is necessary to measure the engine performance by applying a variable load at a constant speed (2000 r/min). During each run, fuel consumption and exhaust gas temperature were measured. In this setting the engine cooling system using the non-standard Shell and Tube Heat Exchanger. The water supplied through a central water circulation system (figure 46). Water circuit connected as well to the dynamometer (figure 44); water is the perfect fluid refrigerating medium. To have an adequate cooling water volume; water should be of appropriate value, temperature, and pressure to allow the sufficient unceasing volume to flow through the apparatus.

Aston University

Illustration removed for copyright restrictions

Table 16: Engine specification [83].

Figure 44: Engine testing platform before modification.

For the engine or the dynamometer to maintain control, water and pressure should be sufficiently constant. Regarding flow rates, it is an excellent preparation to bind the temperature rise of the refrigeration medium through the engine water casing to about 10 °C. The flow rate is significant to the dynamometer as well; it can be ascertained by the extreme tolerable refrigerating water outlet temperature. The flow rate is imperative to sidestep deposition of weighbridge on the internal overlays of the device. In the case of the Hydraulic Froude dynamometer the cooling medium (Water from the main line supply) should not exceed 70 °C as leaving temperature; unlike Eddy current dynamometer, the hydraulic machine creates heat straight within the refrigerating water.

In addition to that, Dynamometer was lubricated, calibrated and tested prior to the engine test. Calibration was done as follow:

- The dynamometer was unloaded by moving the sluice gate control wheel entirely to the left (anticlockwise).
- The spring balance was adjusted to point toward 50 lb (mid-point).
- A weight of 2 kg was loaded in the balance weight.
- The dial position was recorded.
- Steps 3 & 4 was repeated until 8 kg weight (Maximum) was reached.
- Weight was unloaded to record the dial position.
- An average of both load and unload result were taken
- The results in lb were converted to kg.
- A table and graph were made to illustrate the calibration result.

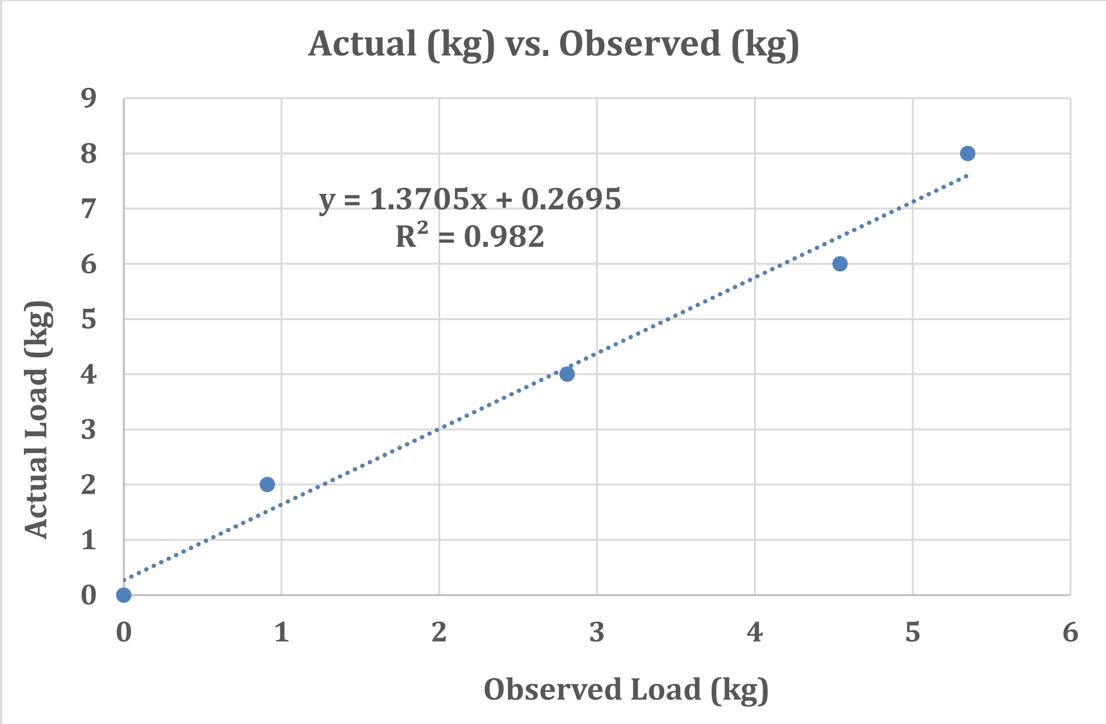


Figure 45: Froude Dynamometer Calibration.

Calibration as figure 45 illustrates that the points are not linear but using the line of best fit would help to average all point of mass in pounds (Ib). Calibration is significant for engine testing to get more reliable results of loads which would be added during runs to measure the engine performance.

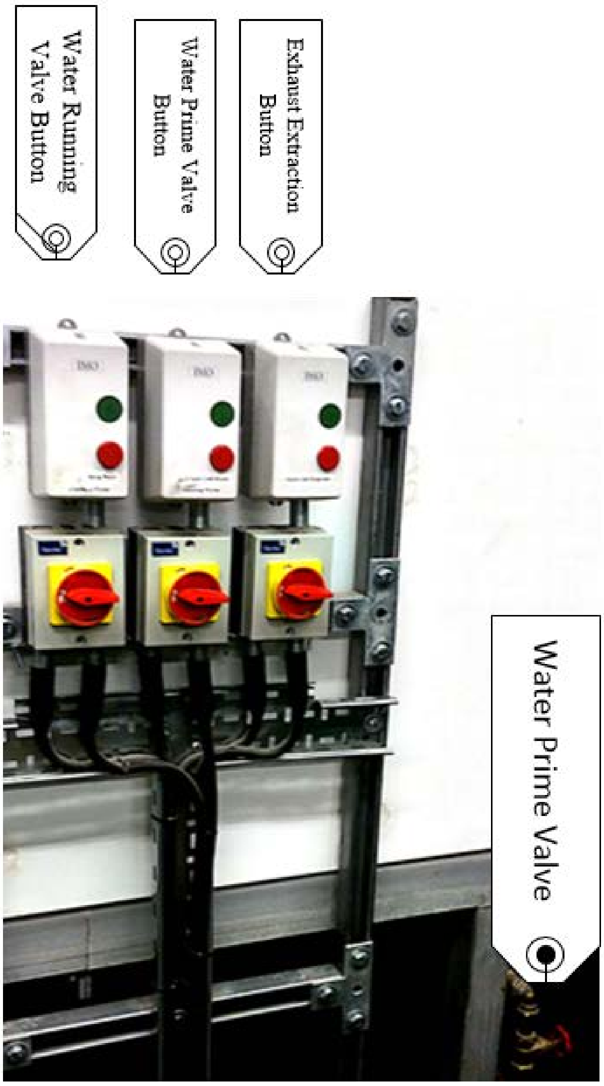


Figure 46: Water and exhaust extractions control keys.

The dynamometer has a bleed-off to drain, to avoid worsening of the water by deliberation of unwanted components. A bleed rate of 1% of system capability per day should be tolerable; if no bleed-off is encompassed, then the full system should be exhausted, washed out and replenished with renewed water. It is essential that the supply compression should be stable otherwise the control of the appliance will be exaggerated [82]. All in all, the water source for an outsized engine experiment setting up is a dedicated assignment not to be misjudged.

3.2.3.1 Fuels line modification

As it has been explaining earlier, the experiment engine used to have only fossil diesel tank connected (figure 47); to test biofuels, another tank was installed. As figure 48 shows, a new tank and set of pipes and valves were installed. A five liters tank was mounted at the height of around two meters on the top of the control panel.

Figure 47: Fuels line modification.

This tank was connected to a three-way ball valve through a fixable pipe (figure 49). The old volumetric flowmeter cylinder was removed. It replaced with a more prominent cylinder (500 ml). It was connected to the ball valve from one side and to a fuel pump from the other side which was attached to a fuel filter. From the filter, the line was linked to the engine using the fixable pipe.

Figure 48: Control panel before modification.

The already installed fossil fuel tank was connected to a 25 liters tank through fuel pump (figure 50). Finally, new valves were installed before and after tanks and the volumetric flower meter to be able to switch between fuels and to measure the fuel consumptions.

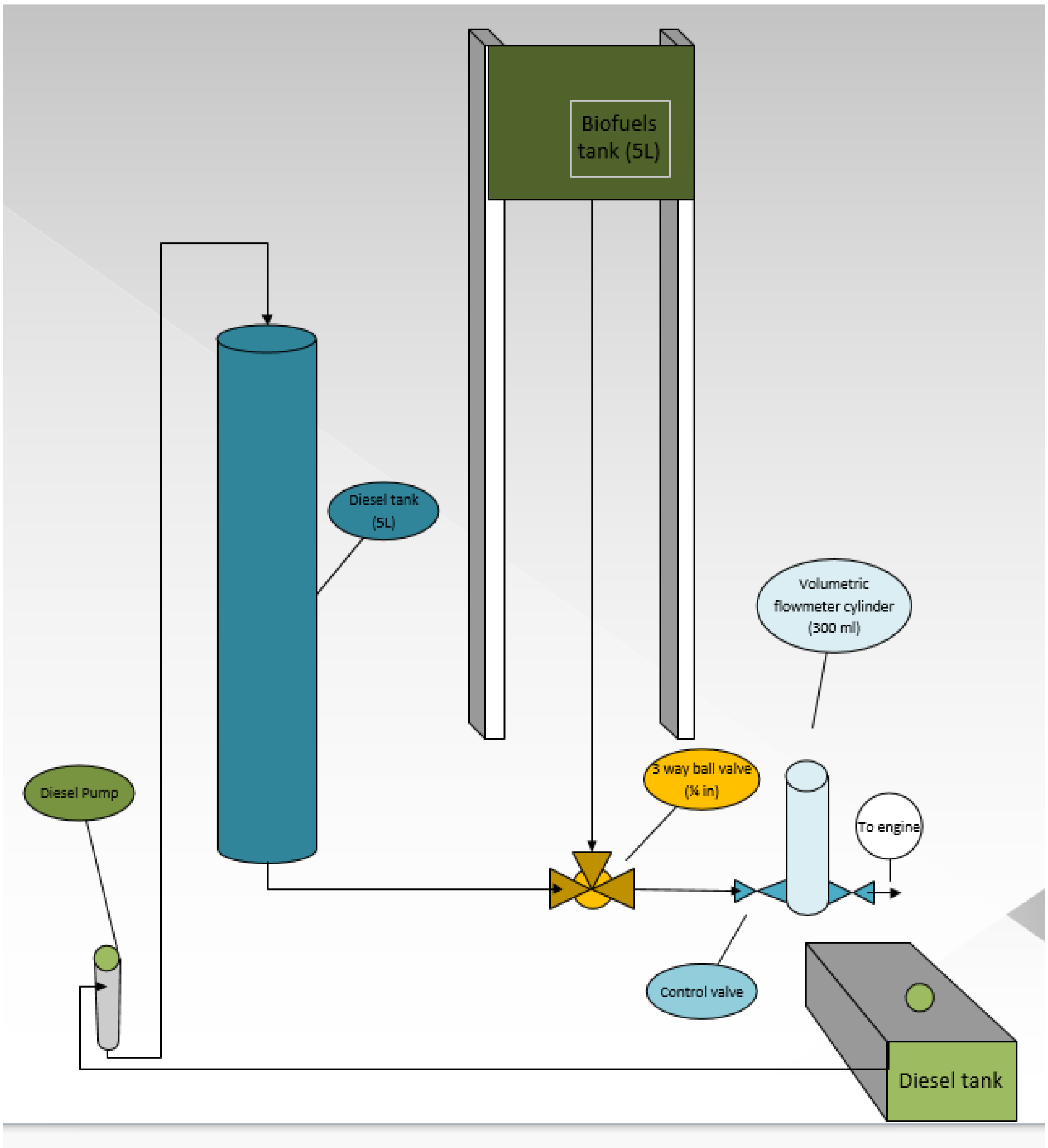


Figure 49: Fuels line change.

The way that this configuration works will be explained in the methodology section. The diameters of fuels pipe were increased to ease the flow of biofuels through the line until it reaches the engine.

Figure 50: Three-way ball valve for fuels is changing.

In addition to that, the line was made shorter by changing the route that the pipe takes towards the engine. The fuels filter near the common real was eliminated, and the line was connected directly to the injections line. In case if there is any air in the system, the line should be disconnected to take the air out manually.

3.2.3.2 Exhaust modification

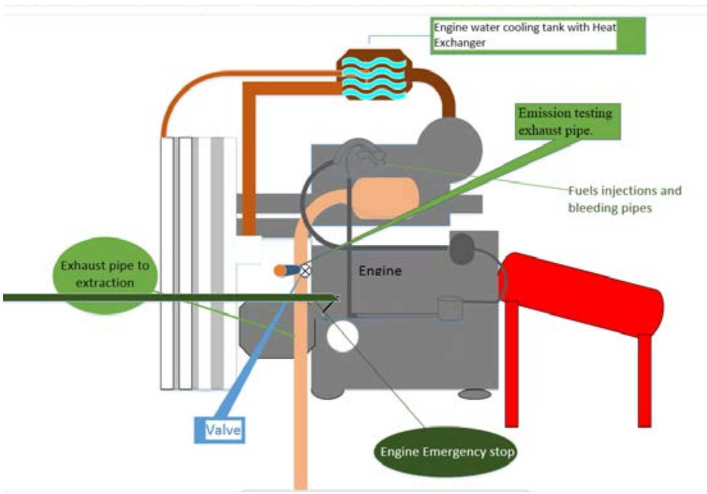


Figure 51: Exhaust modification.

As figure 51 & figure 52 Show, the exhaust pipe was modified by adding another exhaust pipe which is controlled by a valve. This amendment was necessary to measure emission and smoke. The layout and diameter were chosen carefully to fit the sensors of emission and smoke.

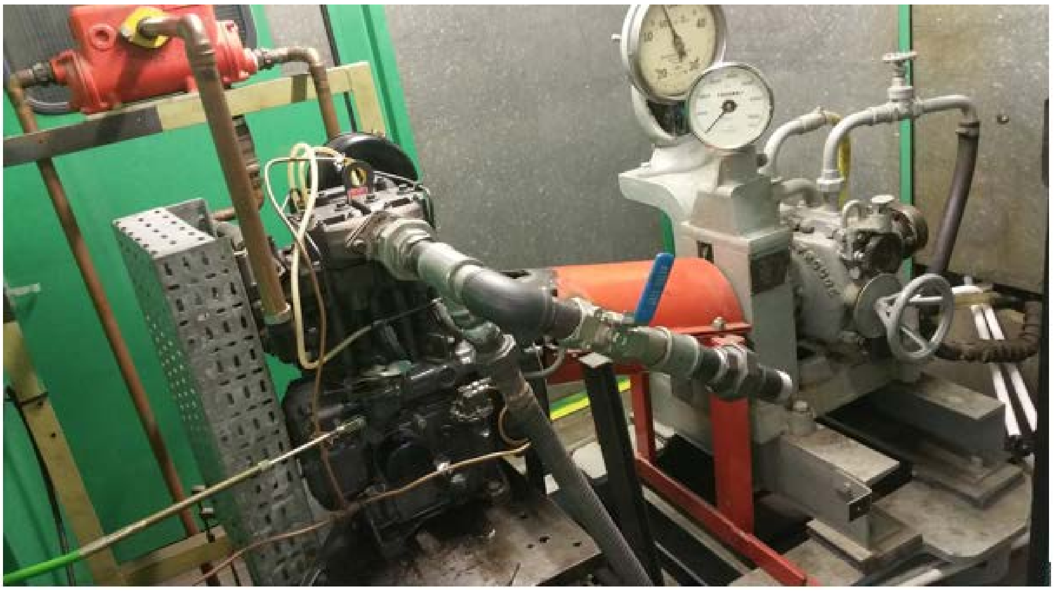


Figure 52: Exhaust pipe modification.

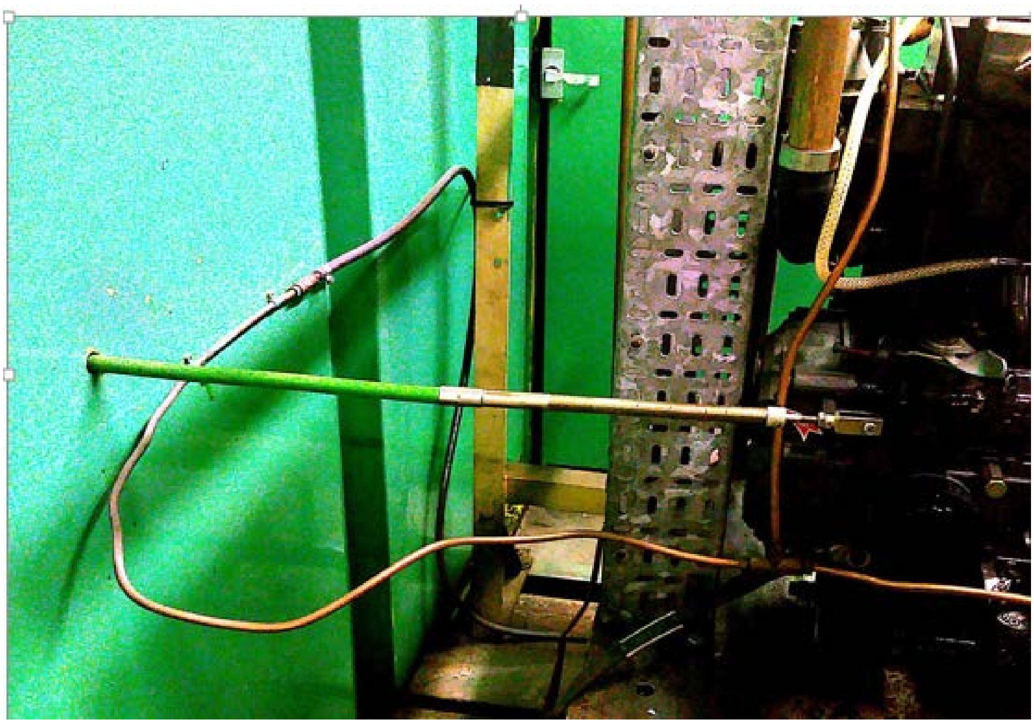


Figure 53: Emergency stop pull off the system.

Lastly, a stop of urgency pulls off system was installed as figure 53 shows; this pulls off system can be operated from outside the engine cabin to shut the engine off.

3.2.3.3 Electrical Circuit modification

As many other installations, an electrical circuit is subject to regulations. In the UK these installation is outlined in the BS 7671, Requirements for Electrical Installations. The installation that has been done in this study is as follow:

- The Green Earthing cable (figure 54) was connected to all electrical devices from the battery negative terminal.

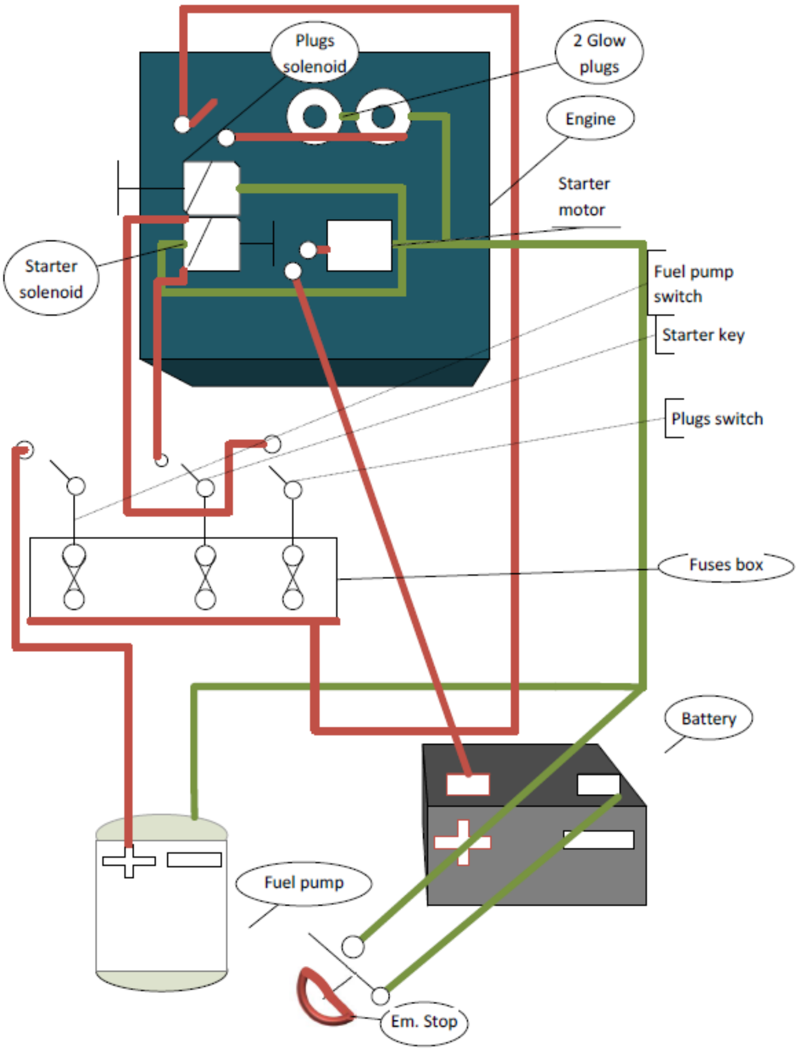


Figure 54: Engine electrical Circuit modification.

- The negative terminal attached to an emergency electrical circuit breaker which was installed outside the engine testing cell cabin (figure 55).
- The fuses box, starter key, fuel pump, fuel pump switch and glow plugs switch are all installed in a control panel outside the engine testing cell cabin.
- The battery positive terminal was connected in parallel to all power cables through the control panel.
- All wires were encased in a protection PVC pipe for extra safety and to keep it away from any oil, fuels or water leakages; whether from the engine or the hydro dynamometer.

Figure 55: Electrical circuit breaker.

In this installation, separate supply lines were used; as well as short supply cables to avoid Conductive Coupling Interference (CCI) [82]. CCI could occur due to the difference in supply voltage between the devices.

To conclude with, it worth mentioning that the system has been integrated with the building management system to make sure that the work in the testing cell does not compromise the safety of cell users or other building users. A comprehensive risk assessment and operation operating procedure has been carried out.

3.3 Methodology

The following methodology will be followed to achieve the aim and objective of this study:

3.3.1. An overview of the electricity and power generation in Sudan.

As a start, this stage will cover the electricity and power generation in Sudan from various resources such as fossil fuel, The Wind, Solar, and Biomass. Then it covered biomass conversion technologies and concluded with legislation and economy of biofuels in Sudan.

3.3.2 Estimation of types and availability of various biofuels in Sudan

In this stage, the investigation will be carried out to find the different types of liquid biofuels available in Sudan. The quantity of each biofuel type will be estimated using various data sources such FAO, World Bank. The output of the stage will be the estimation of biofuels resource potential for electricity generation in Sudan.

3.3.3 Preparation of fuel blends & Characterization

The objective of this phase is to evaluate the quality of the fuel for diesel engine use. Various physical and chemical properties will be measured and compared with the fossil diesel. The fuel blends will be prepared in the lab in 10%, 20%, and 30% blends. Calorific Value will be measured by using Parr 6100 Calorimeter (standard ASTM D420-90) (Figure *40*).

3.3.4 Engine Performance

A 2-cylinder, water-cooled, naturally aspirated, indirect injection Lister Petter engine will be used. This engine is coupled to a Froude Hydraulic Dynamometer to measure power, torque, and speed (figure 44). The exhaust emission will be measured via Bosch BEA 850 emissions analyzer. Modifications on exhaust, fuel supply, and electrical circuits will be carried out. Fuel supply modification, proposed exhaust, electrical supply and are shown in figures 49, 51 and 54, respectively.

The engine starts and shot down with diesel as a precautionary step since biofuel could harm the engine due to the high viscosity. The switch between diesel and biofuel tanks accrues via three-way ball valve (figure 49). Various blends of suitable biofuel applicable for Sudan will be tested, and performance and emission parameters will be recorded and compared to fossil diesel.

To compare the performance and emission of the engine and compare it with Fossil Diesel, some calculation has to be done.

Brake power will be calculated using the flowing equation:

$$Wb\ (KW) = \frac{NW}{6030}(KW)$$

$Wb = Brake\ power$

$N =$ Rotational Speed (rev/min)

$W =$ Brake force(lbf)

$6030 =$ Brake constant provided by the engine manufacturer

Then, using the cylindrical fuel flowmeter (figure 50), the time to consume 100ml fuel will be recorded to calculate mass fuel consumption as follow:

$$Mf\ \left(\frac{kg}{s}\right) = \frac{\frac{\rho fuel\left(\frac{kg}{m3}\right) * 100(ml)}{1000000(ml)}}{t(s)}$$

$Mf = Mass\ fuel\ consumption$

$\rho fuel = Fuel\ density$

$t = Time\ to\ consume\ 100ml\ fuel$

By plotting brake power against mass fuel consumption graph, friction power can be indicated by the best fit line equation. It is assumed that the friction force is constant throughout the test at the constant speed of 2000 r/min; as a result, indicated, power could be estimated from the graph.

$$\dot{W}_f = \dot{W}_{ind} - \dot{W}_b$$

$Wf = Friction\ power$

Wind= Indicated power

Wb= Brake power

After finding the shown power, Brake Specific Fuel Consumption (BSFC) could be calculated. BSFC is the mass rate of fuel consumption per brake power. It heavily depends on density and HHV of fuels.

$$sfc_b = \frac{\dot{m}_f}{\dot{W}_b} \text{ (kg/kJ)}$$

$SfCb = Brake\ Specific\ fuel\ consumption$

Another parameter which will be calculated is the Brake Thermal Efficiency; it is the ratio between energy of fuel combustion and the engine power.

Brake Thermal Efficiency $\eta_{th} = \frac{\dot{W}_b}{\dot{Q}_{th}}$ (%)

$\dot{Q}_{th}$ *=fuel mass flow x calorific value*

Mechanical Efficiency is also useful to calculate since it will indicate the other losses such as friction, water, and oil pumps. It is the ratio of indicated to brake powers.

As figure 56 shows, a thermocouple was installed on the exhaust pipe to measure temperature using a portable temperature meter. This measurement is essential since it shows, during combustion, the cylinder head. The heat could cause damage to engine and turbo components. In addition to that, High exhaust gas temperature also contributes to knocking. In the case of CHP and trigeneration, exhaust gas temperature could be a very significant production; it could be used for heating or cooling by using storage tank and absorption chiller, respectively.

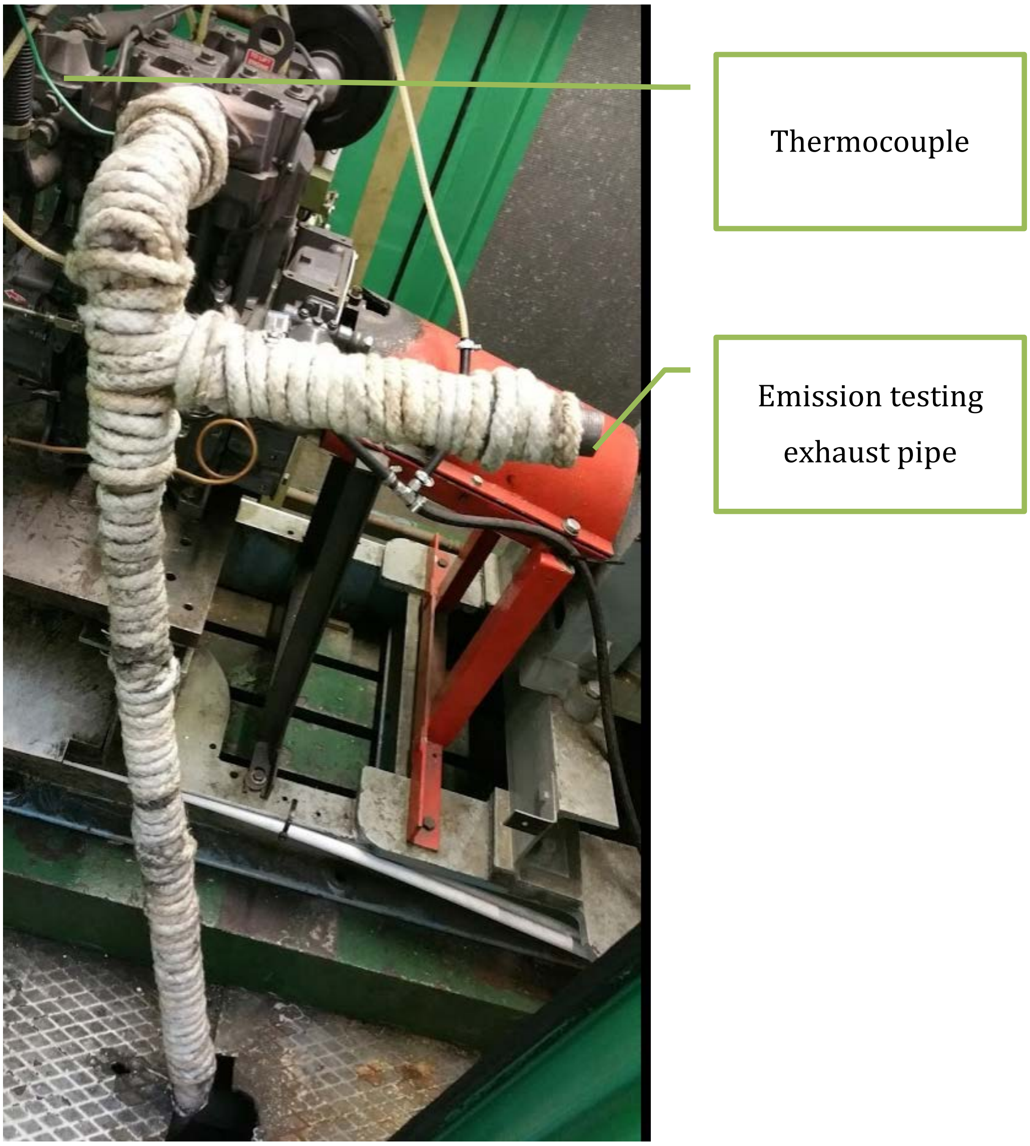


Figure 56: Measurement of exhaust temperature.

3.3.5 Exhaust gas emissions

A modification was done to measure the emission (figure 56). CO, CO2, HC, Lambda, NO_X, O2, and opacity were measured using (Bosch BEA850) emissions analyzer and (Bosch RTM 430). Measuring greenhouse gas (GHG) emissions is significant to evaluate the advancement of atmospheric contamination of all fuels under test.

3.3.6 Recommendations on sustainable biofuels for Sudan

Based on the results obtained from above, recommendations will be made on the sustainable biofuels for electricity generation in Sudan.

3.4 Conclusions

This chapter presented a detailed description of the experimental settings and Methodology. The detail of fuels preparation and characterization was discussed in section 3.2, while subsection 3.2.3 consist of the engine rig setting modification including Fuels line, Exhaust pipe, and Electrical Circuits. This subsection was concluded with the Testing Operation Procedure and Risk Assessment.

Subsection 3.3 was left for methodology. It started with an overview of the energy and electricity generation in Sudan from various resources, followed by an estimation of types and availability of biofuels in Sudan. Further, the preparation testing fuels were discussed, and the chapter concluded with a detailed description of the way that, engine performance will be conducted, and recommendation based on the results will be given for any future work.

Chapter 4: Literature review

4.1 Introduction

Suitable plant oil could be combusted in IC engine in three different ways: as it is, blended with diesel or after converting to biodiesel through transesterification.

Aston University

Illustration removed for copyright restrictions

Figure 57: illustration of the process of biodiesel production [67].

The production of biodiesel from raw vegetable biofuels and fats is well established. The most use of neat vegetable biofuels to biodiesel include; soybean, palm, rapeseed, Jatropha, castor, cottonseed, Neem, sesame and peanut. Figure 57 demonstrates the process of biodiesel production from different biomass.

4.2 Jatropha Curcas Biofuel

Jatropha curcas plant initially comes from Central America[48] and due to the similarity of whether it has been adopted in many tropical countries such as India Nigeria and Sudan. It can cultivate in a different sort of raindrops schemes starting with 250 up to 1200mm annually. Depending on the rainfall, it can be planted in three distinct way; 1) At an area of 2 meters by 2 meters 2) At an area of 2.5 meters by 2.5 meters, or 3) At an area of 3 meters by 3 meters. One of its useful advantages is that it grows in negligible lands with little nourishment content, but it necessitates soils that drain and ventilate well[74].

The process of biodiesel production in Sudan is still in it is an initial stage, nevertheless that Sudan is prosperous with vegetable and plant biofuels. Recently, Sudan started a project to produce biodiesel from Jatropha plant. The reason for choosing Jatropha plant is that there has been a numeral example of successful projects of high-quality biodiesel production from it is seeds and seedcake around the globe[42][48][71][72][73].

Table 17: Differences between Properties of Jatropha's neat biofuels, Jatropha curcas biodiesel and standard specification [48].

Aston University

Illustration removed for copyright restrictions

In addition to the advantages above of Jatropha curcas Table 14 shows the physical and chemical properties of Jatropha biofuel in comparison with its biodiesel and the ASTM D 6751 and EN 14214 standards. The table shows that all the properties of Jatropha Methyl Esters (JME) is closer to the standards except flash point and water content which are higher than the level by around 50% and

In an investigation with Jatropha curcas neat biofuel and biodiesel in a CI engine[84]; near biofuel and biodiesel were blended with diesel to reduce viscosity then the mixtures in various ratios were characterized and tested; the following result was obtained: 1) Standard characterization showed that the increase of diesel percentage was proportional to decrease in viscosity. 2) The rise of the blends temperature was also commensurate with the reduction in thickness. 3) At the brake horsepower (BKW) range 0 – 3.74, it was observed that the specific fuel consumption (SFC) was reduced however a load above 3.74 tended to increase it. 4) In around the same previous capacity range the thermal efficiency increase and started to decrease above BKW of 3.078. 5) BKW in the previous range tended to increase the exhaust gas temperature of the oil, but it began to decline by increasing diesel in the blends. The study concluded that the optimum mix regarding viscosity is 30% Jatropha biofuel. About engine performance; the acceptable brake thermal efficiencies and SFCs were achieved by blends up to 50%; there for the use of Jatropha curcas of 50% can be used in CI engine without any chief functioning complications.

In addition to the previous study, a comprehensive assessment of using raw vegetable biofuels in CI engine[85] concluded that in particular with a small diesel engine, and in minor percentage has shown great potential with respects to the thermal performance and exhaust discharges. The review recommended more study in the same area. More recent attention has focused on the use of raw vegetable biofuel in CI engine. A recent technical review and life-cycle analysis[86] reported similar results to[84] and [85] in showing the potential of utilizing new plant biofuel in CI engine.

All in all, besides Jatropha curcas, Sudan has another potential such as cottonseed, castor, and neem biofuels as first generation feedstock for transesterification and all the edible biofuels that were mentioned earlier such as peanut, sesame sunflowers as second generation feedstock by using factories residues.

4.3 Cottonseed Biofuel

Implementation of cottonseed (Gossypium hirsutum)[87] biofuel in CI engine going back to study in 1940. This systematic engine testing study showed higher fuel consumption compared to diesel[88]; regarding performance, this study showed that there were problems regarding carbon residues, oxidization and pour point in using it as a fuel. Since then researchers thought about conversion to biodiesel to eliminate those performance problems.

In the recent years, there has been an increasing amount of literature on engine testing with cottonseed biofuel[72][89][90][91][92] [93]. Compared to sunflower 96.8%, corn 97.2%, and soybean 97.9 %; cottonseed biofuel produces (by mass) 97.6 % methyl ester by transesterification. Moreover, cottonseed has the advantage of being non-edible[89]. The properties of neat cottonseed biofuel and cottonseed methyl ester are comparable except the viscosity which is around four times higher in neat cottonseed biofuel.

Table 18: The properties of some neat vegetable biofuels and its methyl esters [89].

Aston University

Illustration removed for copyright restrictions

A comprehensive review in 2004,[89] on CI engine tastings, showed that the thermal efficiency of cottonseed biofuel was equivalent to that of fossil diesel with the unimportant quantity of power loss. Particulate emissions were higher than diesel but with a reduction in NO_x. The study concluded that cottonseed biofuel could be used us raw in an engine with minor modifications, while its methyl ester can substitute diesel. Four years later another review[90] on biodiesel production from different feedstocks showed that the properties of cottonseed oil are suitable for CI engine and perfect for biodiesel production; while the cloud and pour points are too high for other inexpensive feedstock such as Tallow, Yellow grease, and Soap stock methyl ester. The study concluded that more research should be done to improve the cold-flow properties of cheap biodiesel's feedstocks. This conclusion implies that cottonseed biofuel is among the valuable feedstock.

In 2009, Nabi et al. produced methyl ester from cottonseed biofuel. The production of maximum biodiesel was 77%; this achieved by 20% methanol, with 0.5% NaOH and 55 °C reaction temperature. The biodiesel was blended with diesel in B10 (10% biodiesel and 90% diesel) and B30% before evaluation in a single cylinder, water-cooled, NA, 4-stroke, DI diesel engine. The engine was joined to a dynamometer. The study demonstrated that the B10 showed less CO, PM, smoke discharges compared with diesel; the PM and smoke emissions were 24% and 14% respectively. B30 reduced CO by 24% while it surged NO_x emission by 10%. Regarding thermal efficiency, there was negligible reduce compared with diesel. The study attributed that to the slight difference in the heating value of the blends in addition to other properties effects such as higher viscosity, higher density, and instability[92]. Another study[94] on viscosity, surface tension and volume flow rate of some oils showed that the surface tension of cottonseed biofuel is 24.13 mN/m. High surface tension makes atomization difficult. This in return leads to higher spray tip penetration as a result that leads to poor combustion. In term of emission, poor combustion produces smoke and other pollutants[95].

As a conclusion, cottonseed biofuel has shown real potential as replacement of or blend with diesel. It can be used as a biofuel with some engine modification or as biodiesel without any engine modification.

4.4 Castor Biofuel

The seed from castor (Ricinus communis) plant is the resource of castor biofuel. Initially, it comes from East Africa especially Sudan; it grows as a wild plant. Such as Palm oil tree which has been planted in Malaysia and Indonesia, castor plant has been introduced to another tropical land such as India and become more known there than in Africa.

Castro plant, (Ricinus communis L. (figure 58) originates in humid countries. It produces in volatile and sub-tropical arid regions[96]. It can reach the height of 10 m, and it can reach the age of 4 years. The previous study illustrates that castor plant has reached 60-120 cm in the first year. One of the big challengings of castor plant is poisonous. Hence carefulness is required during gathering and processing.

Figure 58: Castor plant [96].

In many countries, the whole process from planting and harvesting to seed pressing is done by machines. The biofuel yield per seed was 30-36% when cold pressed and 38-48% when warm pressed (> 70 °C). The Globe average of land seed yield is 1.1 t/ha, but in a very excellent condition, it can increase up to 5 t/ha. One hectare could reach 2000 kg biofuel. It is one of the seeds planted with high biofuel yield potential; nevertheless, worldwide oilseed trade market is less 0.15%[96].

Laureano Canoira et al.[97] Have studied the production process and synergistic effects of Fatty acid methyl esters (FAMEs) from neat castor biofuel. The study used methanol and sodium methoxide as catalysis during the transesterification process. The study suggested that FAMEs cannot be used in engine without blending due to high viscosity and high water content (*Table 19*); thus blends with diesel have been prepared, and their properties were characterized The study concluded that the blend of 40% of FAMEs meets most of the specification of the EN 590 standard (Table 20).

Another study[94] on viscosity, surface tension and volume flow rate of some oils showed that the surface tension of Castor biofuel is 14.89 mN/m. High surface tension makes atomization difficult. This in return leads to higher spray tip penetration as a result that leads to poor combustion. In term of emission, poor combustion produces smoke and other pollutants[95].

Aston University

Illustration removed for copyright restrictions

Table 19: Castor biofuel feedstock properties [97].

Aston University

Illustration removed for copyright restrictions

Table 20: Properties of a blend of FAME and diesel [97].

Aston University

Illustration removed for copyright restrictions

N.L. Panwar et al.[98]have prepared castor methyl ester (CME) by transesterification using potassium hydroxide (KOH) as a catalyst instead of sodium methoxide utilized in the previous study. In addition to characterization, this study used CME blends with diesel in four strokes, single cylinder variable, compression ratio type Kirloskar diesel engine.

The study concluded that CME blends exhibited performance characteristics comparable to diesel components. In contrast, with the previous study[97], this study showed that pure methyl esters from neat castor biofuel could be used in the engine. However, it agreed with this study that blends with diesel are more favorable. In 2011, another study[99]which compared the production of biodiesel from neat castor biofuel through conventional and in situ processes. It concluded that both procedures are feasible, but since the study worked with low-quality biofuel, the traditional method is more promising.

4.5 Neem Biofuel

Neem or Azadirachta indica is a native South East Asian seed[100]. It is not poisonous. A recent study[101] showed that neem biofuel properties are suitable for utilizing in CI engine as raw or its methyl esters. In this study, a Neem Oil Methyl Esters (NOME) have been prepared in a laboratory. 06% of anhydrous lye catalyst (NaOH), 20% of methyl alcohol (CH_3OH) were used with moisture-free neem biofuel. The blend was heated to 55-60 °C and then left to settle down by gravity to 24 hours.

Table 21: NOME and Diesel properties [101].

Table *21* shows the properties of diesel and NOME, which is almost the same except oxygen content; this indicates that there is a little amount of water in the NOME, but it has been removed by heating before it enters the engine. In the second stage of this study, the NOME was blended with diesel and tested in a four-stroke naturally aspirated undeviating injection diesel engine. The study concluded that the blends comparing to diesel has shown lower carbon monoxide (CO) and smoldered emissions but higher oxides of nitrogen (NO_x) emission, however, this was reduced when Exhaust Gas Recirculation (EGR) was used. All in all this study was suggested that neem biofuel could be a substitute clean diesel. Another study[102] supported the previous finding when neem biofuel was used in an investigation together with other non-edible biofuels and Producer gas. In this study, investigations have been done on a single cylinder, four-stroke, direct injection, water-cooled CI engine using neem biofuel functioned in single fuel mode. Then in dual fuel mode in combination with Producer gas from downdraft moving bed gasifier which attached to the engine. In this dual mode, the study was conducted in a variance injection timings and injection pressures using a modified carburetor. The study concluded regarding neem biofuel:

- In both cases no significant engine modification required.
- In single fuel operation, the thermal brake efficiency was 26% which is higher than a dual mode of 17%.
- Smoke/NO_x emissions in dual mode are lower than single mode while HC/CO emissions are high.

Azam et al.[103] Investigated 75 plant types which have 30% or more fixed biofuel in their seed/nut. He suggested that neem biofuel was one of the most appropriate biofuels for biodiesel usage. In contrast [100] indicated that neem biofuel encompasses vast quantity of free fatty acids; there for the study esterified it with an adapted synthesized phosphoric acid. It concluded that the acid value was condensed from 24.4 to 1.8 mg KOH/g biofuel. The study advocated that this catalyst is a potential replacement for conventional homogeneous catalysts that have been used in other successful studies such as[101][102][103]. A recent review[104] investigated the production of biodiesel from neem in India. The study suggested that there are around half million tons seed and around 100 thousand tons of biofuel per year. It added that neem tree has multipurpose uses; one of those is the extraction of ‘Azardiratchi’ from its biofuel for therapeutic purpose then the rest can be esterified, Table *22* shows the properties of neem biofuel and its ester.

Table 22: Characterization of neem biofuel and its ester [104].

Aston University

Illustration removed for copyright restrictions

This study indicates that Neem initially grows in India and Burma, but it can be found in more than 40 countries such as Nigeria and Sudan. The study concluded that neem demonstrate extreme perspective as non-edible biodiesel feedstock that can be implemented in a combined method since it has multipurpose consumptions. Dhar et al.[105] investigated the production of biodiesel from high- free fatty acid and its enactment, emission and combustion characterization in a single cylinder DICI engine. They come to the conclusion that minor blends of up to B20 can be utilized in unchanged CI engine without any concession in engine performance and emission characteristics.

Regarding neem biofuel extraction, there are numerous ways; such as mechanical pressing, supercritical fluid, and solvent extraction. Each type has its advantages and disadvantages[106]. It has been demonstrated by the previous study, that using solvent extraction provides greater harvest and fewer scrambled biofuel than mechanical removal, and relative little operational cost compared with supercritical fluid extraction. The study extracted 41.11% using ethanol and 44.29% using n-hexane as solvents at 50 °C and 0.425-0.71 mm particle size. The study concluded that the upsurge of temperature has reduction effect of iodine value but it triggered saponification, acid, and peroxide value turn out to be greater. It implied that the rise of harvest reduces the quality of the biofuel. Ragit et al.[107] investigated the engine performance and exhaust emission characteristics of a single cylinder 4- stroke CI engine run on the esters of hemp and neem biofuels using conventional diesel as a reference. Regarding neem biodiesel, the study observed that there was a reduction of 6.06% in $NO_{x,}$ 2.59% in HC and 18.39% in smoke. It concluded that both hemp and neem biodiesel could be consumed in CI engine without any engine modification; the study, however, inclined towards hemp biodiesel. A review concerning indigestible vegetable biofuel and their derivatives for alternative diesel fuels in CI engines[93] argued that Neem is among the biofuel that 20% of it can be used in CI engine without any modification. The study reported that the oil content of neem seed and kernel are 20-30 and 25-45 (at %) respectively.

Thus far several studies have confirmed the effectiveness of using neem biofuel in CI engine as raw or its ester. These are somewhat encouraging findings, and it shows that rural communities in Sudan can benefit from neem biofuels besides the present use of the tree as windbreak and shelterbelt.

4.6 Peanut Biofuel

Peanuts biofuel is also known as groundnut biofuel derived from peanuts. Awareness of use of Peanut biofuel in CI engine is not recent, having possibly first been described in the first years of the 19th century when Rudolf Diesel invented and tested his very first engines[86].

The previous study showed that the properties of peanut biofuel are closer to Diesel apart from viscosity which is a common problem in all vegetable biofuels. In 1983, a comparison study[108] of fuels blends was conducted. This study used soybean, peanut, cottonseed and sunflower biofuels blends with diesel in a CI engine. The study concluded that the performance and emission characteristics of all blends were more or less comparable (Table 23).

Table 23: The properties of some edible and non-edible plant biofuels and diesel [86].

[a] At 38 °C.

Another study[109] conducted in the same year in a single cylinder water-cooled dual fuel engine, agreed with the previous survey and recommended the following: 1) to minimize the effect of vegetable biofuels on the nozzle, regular cleaning is necessary. 2) To avoid fuel line blockage engine should be started and stopped with diesel. A third study[110], evaluated the effects of blending peanut biofuel and sunflower with diesel in a single cylinder engine. The study noticed that: 1) the increase of carbon discharges is proportional to the growth of biodiesel percentages. 2) The calorific value of biodiesel is less than diesel. A review about biodiesel [91] concluded that high viscosity of biodiesel caused injector coking and contaminated the lubricating in addition to that, unburned hydrocarbon, as well as NOx, are higher with biodiesel compared to diesel.

A wide-ranging assessment by Hossain and Davies[86], about plant biofuels usage in CI engine, concluded that the life-cycle output-to-input energy proportion of neat vegetable biofuels is estimated at six times greater than diesel and between 2-6 associated to the resembling biodiesel. Moreover, vegetable biofuels have the uppermost potential of dropping life-cycle GHG emissions compared with diesel and biodiesel.

All in all, peanut biofuel has the potential of replacing diesel. Several studies showed that it is properties are suitable for CI engine. A blend of 20 % with diesel would run the engine without any damage to engine parts. Being an edible biofuel and its high price could make implementation more complicated.

4.7 Sesame Biofuel

Sesame (Sesamum indicum L) is a comestible oilseed which planted in many humid and subtropical regions of the world such as Sudan, India, China, Burma[111]. Sudan is the major exporter and the third regarding production worldwide[112]. Sesame biofuel has long been a question of keen interest in a wide range of fields. The previous study[112] suggested that sesame is a crucial player in person nourishment.; it has pleasurable taste; it positions second after olive regarding dietetic value.

Table 25 Shows the physical and chemical properties of the ten sesame seed cultivars, Aswad, mixed, 3015, local white and kenana1is the Sudanese genotypes and the other five types is the US genotypes[112]. Regarding biofuels, Banapurmath et al.[113] have compared sesame neat biofuel methyl ester, Honge and Jatropha biofuel effect on running a single-cylinder, four strokes, direct-injection, CI engine. They investigated the thermal brake efficiency, combustion duration, ignition delay, HC, Co, $NO_{x,}$ smoke opacity and heat release rates. They concluded that sesame biofuel shows high thermal efficiency and low emissions in comparison with Honge and Jatropha biofuel. Evidence showed that viscosity is among the most important chemical properties for using sesame biofuel. In an experimental study, Altun et al.[114] investigated blends of 50% sesame biofuel with 50% diesel to determine engine performance and exhaust emissions characteristics. The test engine is a Lombardini 6 LD 400, one cylinder, four – stroke, air-cooled, direct injection diesel engine. Blending aims to reduce the high viscosity of sesame biofuel. The study concluded that the blend could be used as a fuel without any modification indirect injection diesel engines. In a comprehensive review which includes sesame biofuel, Hossain and Davies[86] suggested that raw plant biofuel have a significant advantage over conventional diesel with regards to life-cycle energy and greenhouse gas emission. A recent study conducted in Nigeria[63] shows that the cultivated area of sesame was 196 thousand hectare with an estimated biofuel production potential of 136 million liters. This study supports the view that Sudan can be one of the major producers of biofuels from sesame since it is producing 60% of the world production[112]. A recent review, which includes sesame biofuel[85] showed that the usage of straight vegetable biofuel in CI engine with lower capacity is promising when used in small percentage blends with conventional diesel. Table 25 shows the properties of sesame oil together with other vegetable oils. The most remarkable properties comparing with diesel is the viscosity and heating value. The viscosity can be resolved by preheating. The lower heating value, which is due to the existence of chemically bound oxygen, as[85] stated; can be compensated with the oxygen benefit during combustion. This study investigated the use of raw vegetable oils in a diesel engine; nonetheless that the survey has focused on Indian conditions, but it has come to a conclusion which is beneficial for tropical countries such as Sudan. The study concluded that utilization of raw vegetable biofuel or as a blend has a high potential. The study argued that CI engine in these countries: 1) Easier to adapt to the properties of raw vegetable biofuels. 2) Less viscosity related problems due to the tropical temperature. 3) The stationary CI engine is running at low speed. It can be added to those arguments that since the CI engine are old local people have built skills and knowledge which enable them to make their parts to avoid the high prices of import.

Table 24: Sesame seed biofuel physical (A) and chemical (B) properties [112].

Table 25: Properties of sesame biofuel in comparison with other biofuels [85].

Atabani et al.[87] In a comprehensive review on biodiesel have shown that sesame is among the first biofuels' feedstocks. The investigation concluded that more than 75% of biodiesel production expenditure goes to feedstocks; this indicates that Sudan could produce biodiesel at a competitive price by using sesame; nevertheless, that Sesame is an export commodity. For some local and global issues exporting sesame is facing some serious challenging; production of biofuels could benefit local farmers and local rural economies[115]. Agriculture is an integral part of Sudan's economy. The estimated annual production of agriculture is 15 million tons[12], and sesame is one of the leading corps. Omar[58] investigated biomass energy and prospect in Sudan. He argued that sesame residue is one of the primary crop residues which is suitable for power generation.

Returning to the question at the beginning of this subsection, it is now possible to state that sesame in Sudan has the potential to be a promising biofuel feedstock.

Chapter 5: Plant oils properties' values and discussion

5.1 Introduction

Properties of plant biofuels have been instrumental in our understanding of its suitability for testing in an engine to investigate whether it can be a suitable replacement for diesel. This chapter shows the measured values and discussion of HHV, Viscosity, Density, and flashpoint.

5.2 HHV measured values and Analysis for all samples

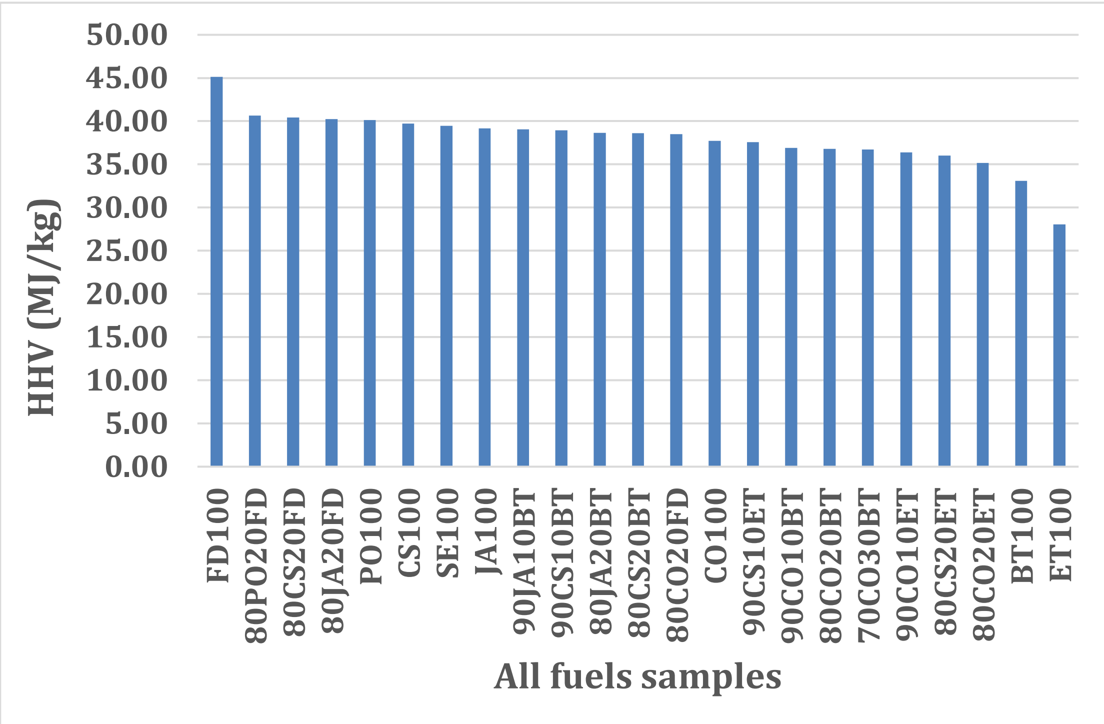


Figure 59: HHV of all samples in order from higher values to lower.

Figure 59 illustrates, HHV of all samples were measured by standards method. It can be observed that all sample possess low HHV in comparison with FD (reference fuel) which has a value of 45.12 MJ/kg.

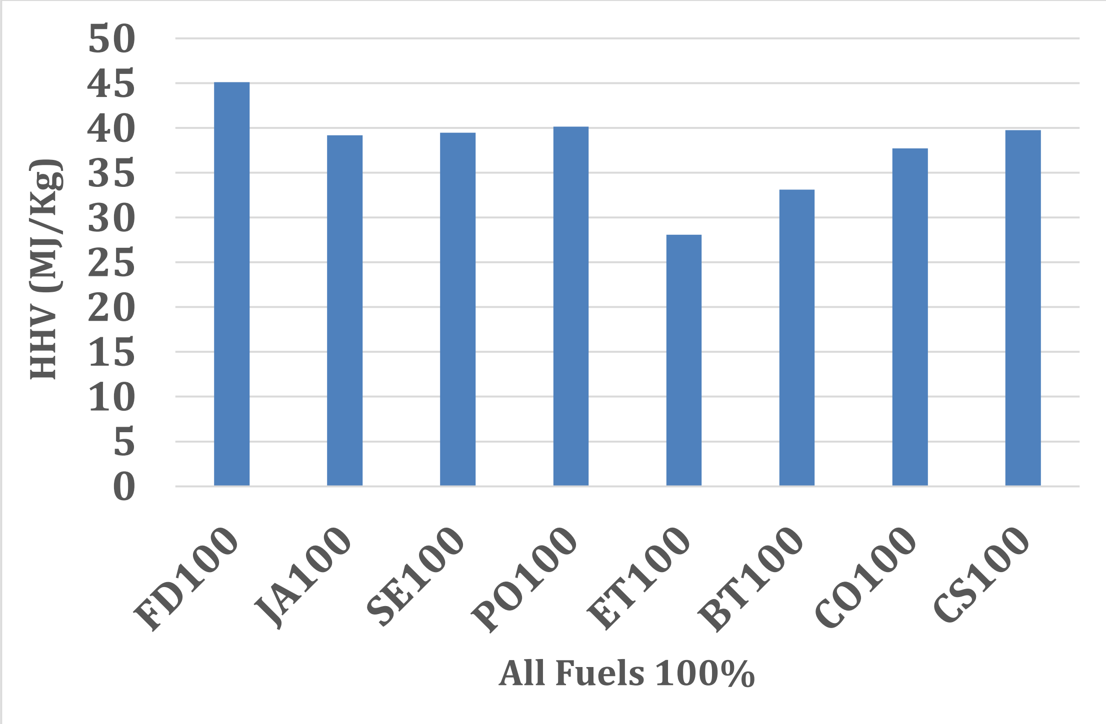


Figure 60: HHV of all pure fuels.

Regarding pure plant oil (figure 60) PO100 has a value of 40.13 MJ/kg followed by CS100, SE100, and JA100 with values of 39.74, 39.47 and 39.18 MJ/Kg, respectively.

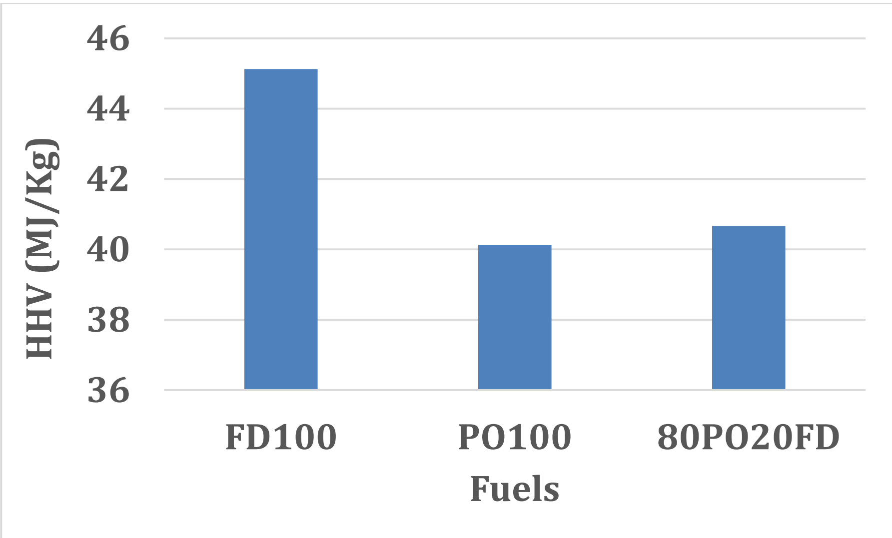


Figure 61: HHV of FD100 with PO100 and its blends.

While among the blends 80PO20FD (figure 61) and 80CS20FD (figure 62) has the closest value to FD with 40.66 and 40.41, MJ/kg respectively, followed by, 40.23 MJ/kg of sample 80JA20FD (figure 63).

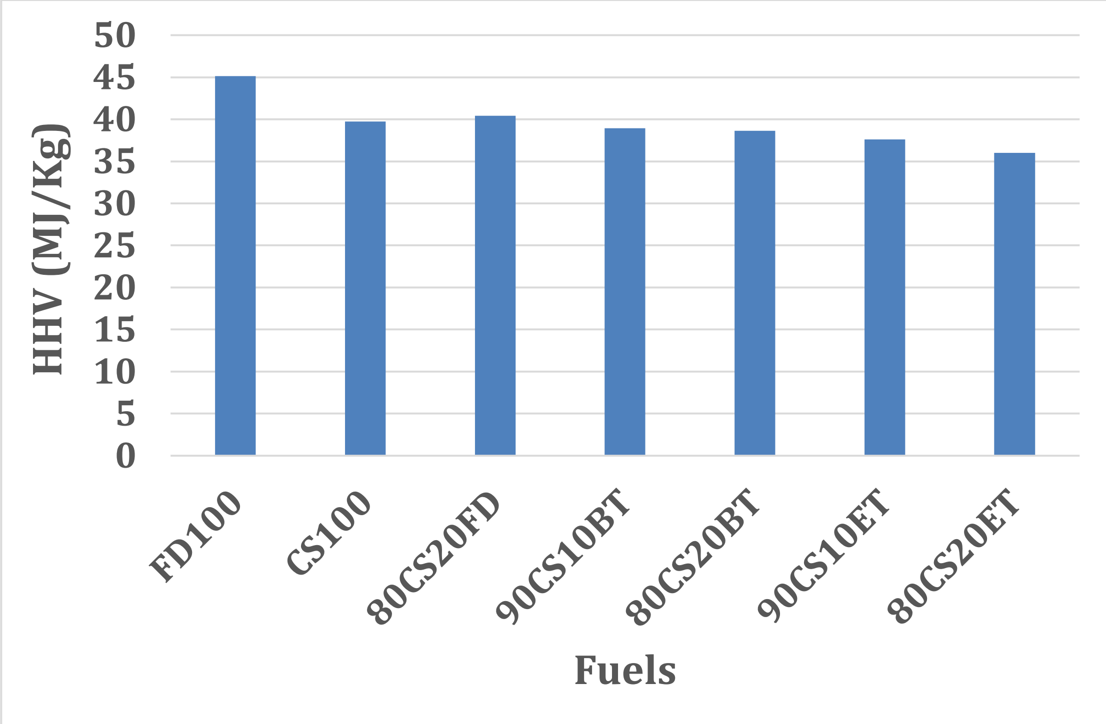


Figure 62: HHV of FD100 with CS100 with its blends.

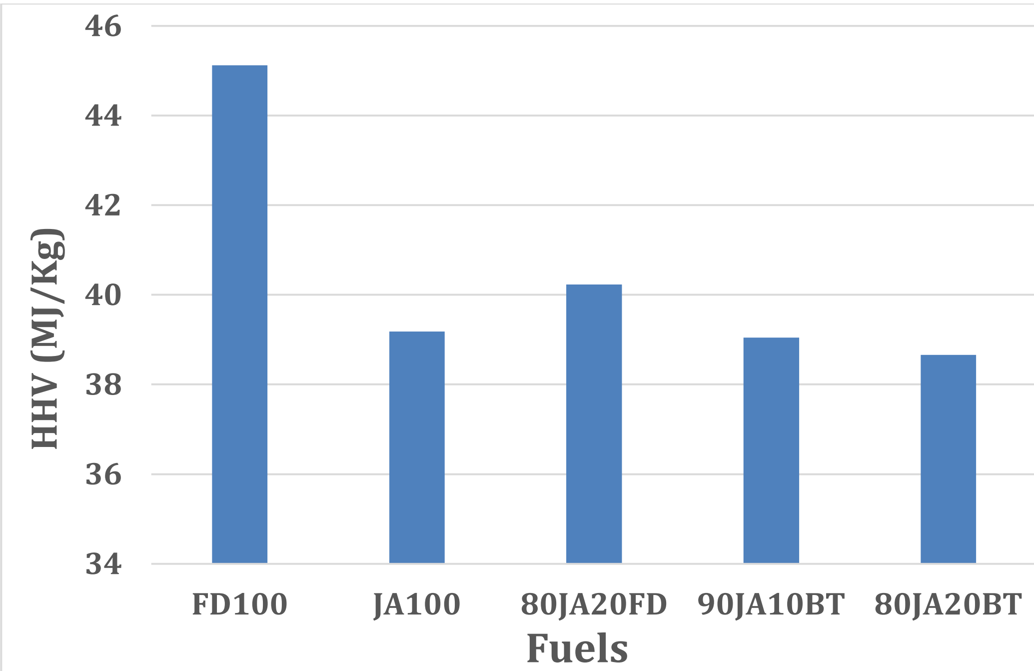


Figure 63: HHV of FD100 with JA100 with its blends.

On the other hands CO100 (figure 64) with a value of 37.71 MJ/kg and its blends, shows the lowers HHV values among all samples. Its results fluctuate between 35.15 MJ/kg of 80CO20ET and 36.78 MJ/kg of 80CO20BT.

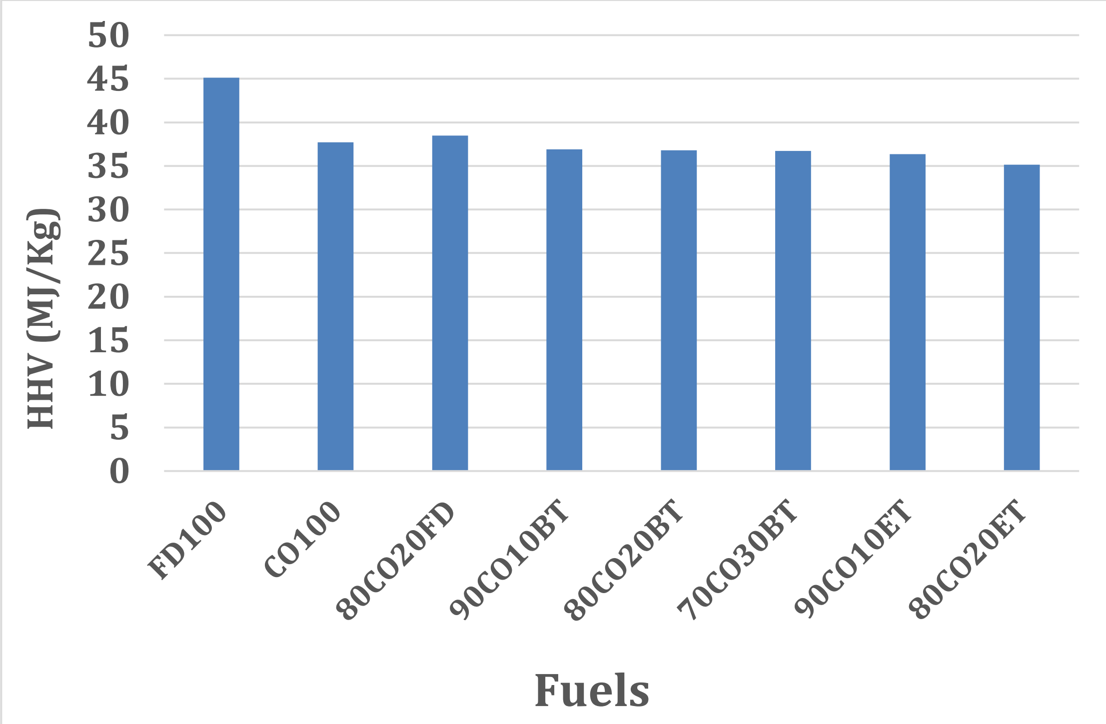


Figure 64: HHV of FD100 with CO100 and its blends.

To conclude with, 80PO20FD, PO100 and SE100 have the highest HHV values among the edible plant biofuels. As the literature has shown, these two plant biofuels are the most popular in Sudanese diet; this reason excludes it as promising biofuels. Sustainability is central to this study. Nevertheless, a future study could investigate the possibility of using waste from both feedstocks as biofuels.

The exclusion of these biofuels makes CS100, JA100 and its blends the best option for an engine testing.

5.3 Viscosity measured values and analysis for all samples

Viscosity values of all sample are higher than FD of 4.39 cSt/s at room temperature and 2.53 cSt/s at 40 °C. The closest pure biofuel to FD viscosity at 40 °C is JA100. Nevertheless, it is around 12 times higher; followed by CS100 and SE100 which is around 14 times greater. CO100 shows, on the other hands, the highest viscosity with around 100 times greater than FD viscosity.

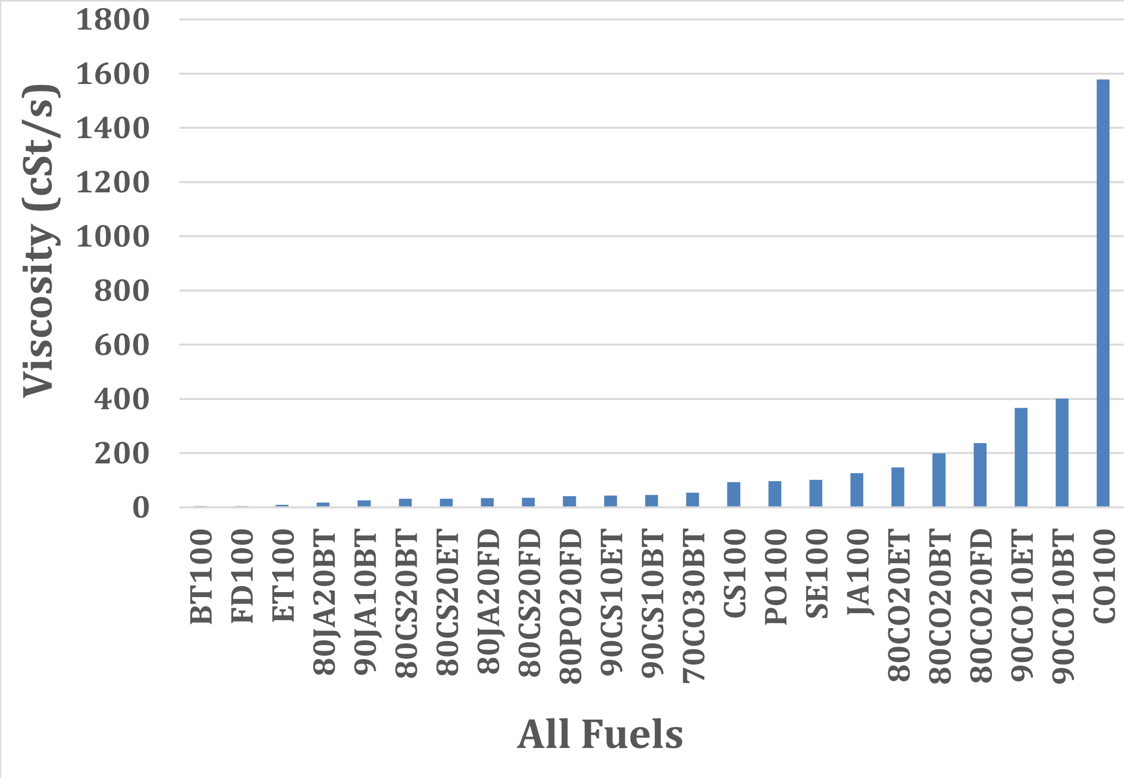


Figure 65: Viscosity of all samples at 14 -25 °C –ASTM D7544.

Among the technic of reducing the viscosity, is mixing with lower viscosity fuels or alcohol. In this investigation, JA100, CO100, PO100, and CS100 were blended with 10%, 20% and 30% of ET100, BT100, and FD100 as figure 65 shows.

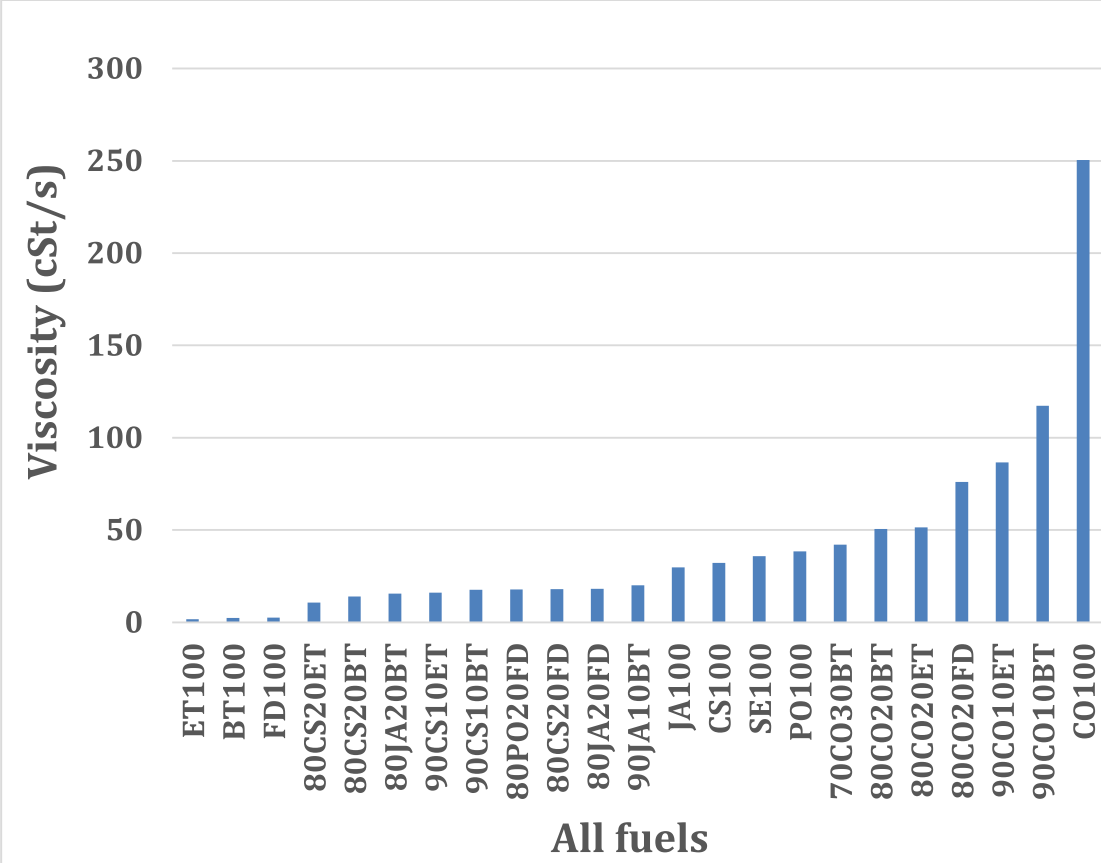


Figure 66: Viscosity of all samples at 40 °C – ASTM D7544.

Another technic is to increase the temperature of biofuel before entering the combustion chamber. As figure 66 illustrates, the viscosity of all sample reduced by increasing temperature to 40°C. The most fuels showed kinematic viscosity in the range between 1.7 – 76 cSt at 40 °C except 90CO10ET, 90CO10BT and C100. The high viscosity of the last three sample could be attributed to the high molecular mass of CO100 which prevent each other from past sliding one other smoothly.

The blends: 90CO10ET, 80CO20ET, 90CO10BT and 80CO20BT have viscosity values at 40 °C varies between 50.58 cSt/s and 117.25 cSt/s which is the superlative case 20 times higher than FD. CS100 blends, in contrast, show viscosity values at the same temperature between 14.06 cSt/s and 17.63 cSt/s.

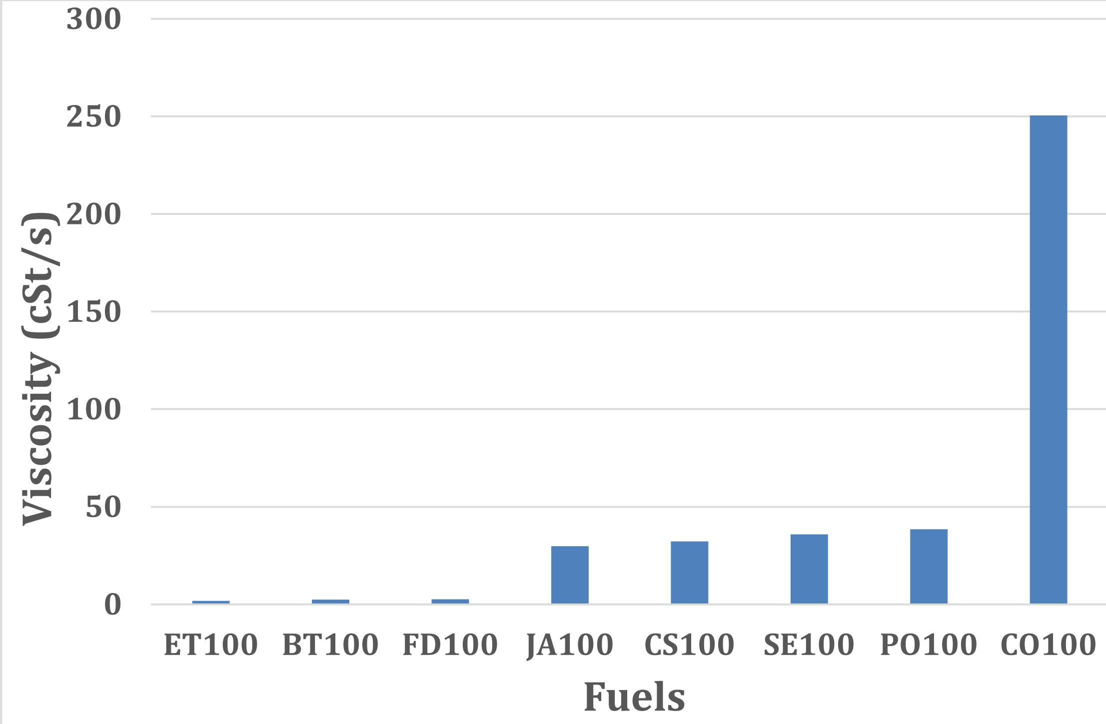


Figure 67: Viscosity of FD100 and other 100% fuels at 40 °C.

Regarding all pure fuels, kinematic viscosity varies in the range 1.7 – 38 cSt at 40 °C except CO100 which is 250 cSt. These values indicate that blends of any of these pure fuels could be suitable for running the engine from viscosity perspective.

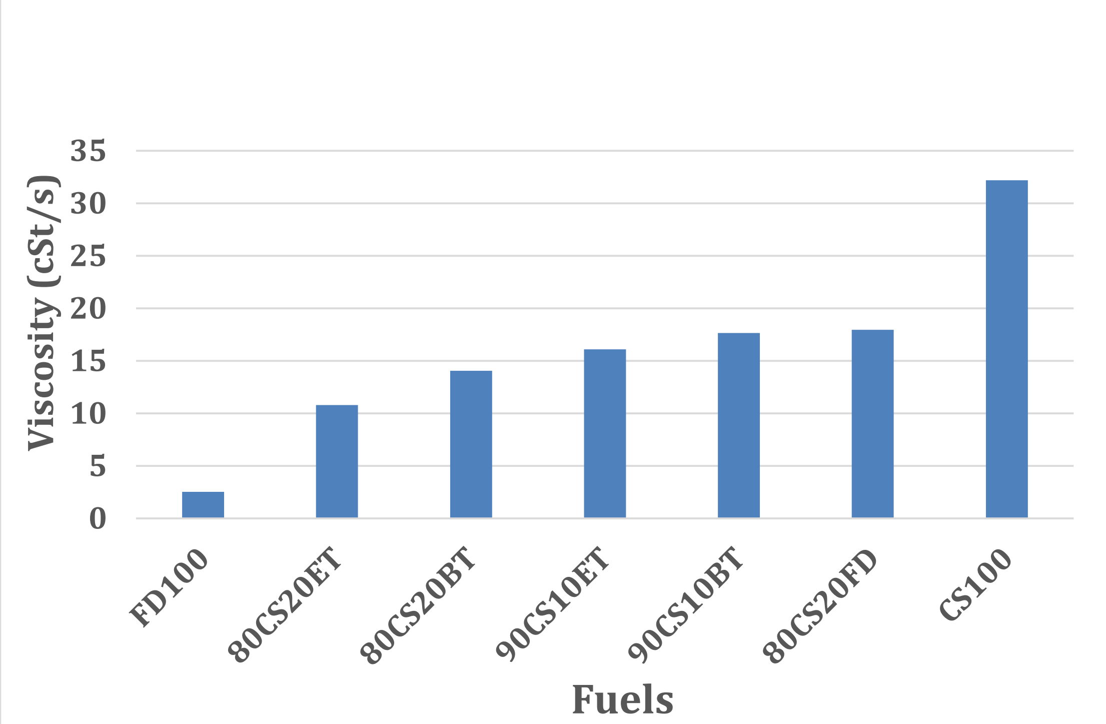


Figure 68: Viscosity of FD100 with CS100 and its blends at 40 °C.

As figure 68 shows, the lowest viscosity in these blends is 80CS20ET with 10.82 cSt/s, but unfortunately, as it was mentioned in section 8.2, it has miscibility problem. The second lower viscous blends are 80CS20BT with a value of 14.06 cSt/s followed by 90CS10ET with a value of 16.09 cSt/s.

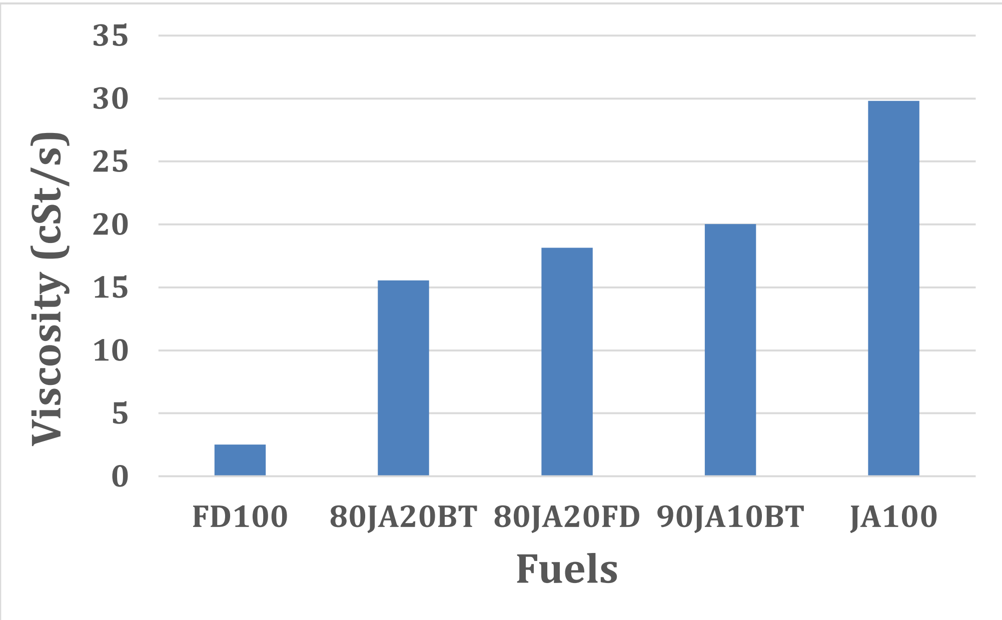


Figure 69: Viscosity of FD100 with JA100 and its blends at 40 °C.

In comparison, JA100 and its blends show the lowest kinematic viscosity (figure 69) it varies in the range 15-30 cSt at 40 °C.

To conclude with, C100 and JA100 with its blends can be tested in an engine if the other properties are suitable while CO100 and its blends show high kinematic viscosity with exceptional of 20% blends of BT, ET, and FD which was shown a viscosity in the range 50-76 cSt at 40 °C.

5.4 Density measured values and analysis for all samples

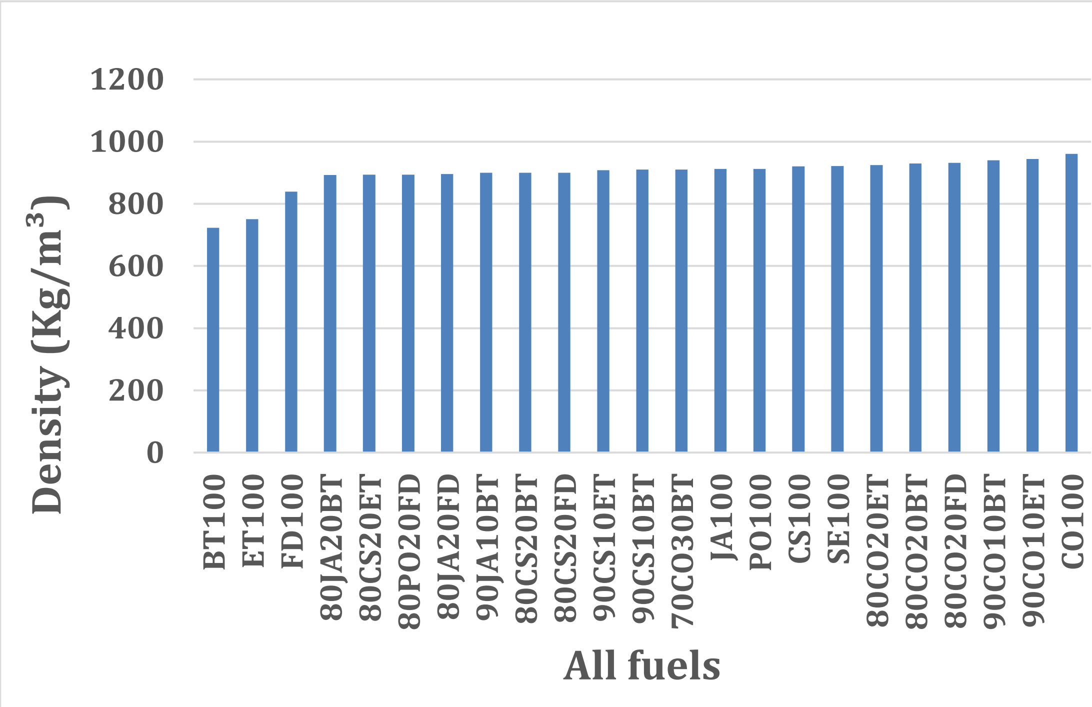


Figure 70: Density of all fuels – ASTM 1298.

The density of plant oil is higher than FD as figure 70 illustrate. FD sample was observed to have a density value of 839 kg/m^3 which is lower than that of all other oil samples in this study.

The density of ET100 and BT100 was calculated using the following formula:

$$\frac{Mass\ (kg)}{Volume(cm3)} \qquad (1)$$

ET100 mass = 30g

ET100 volume = 40cm^3

BT100 mass = 21.7g

BT100 volume = 30cm^3

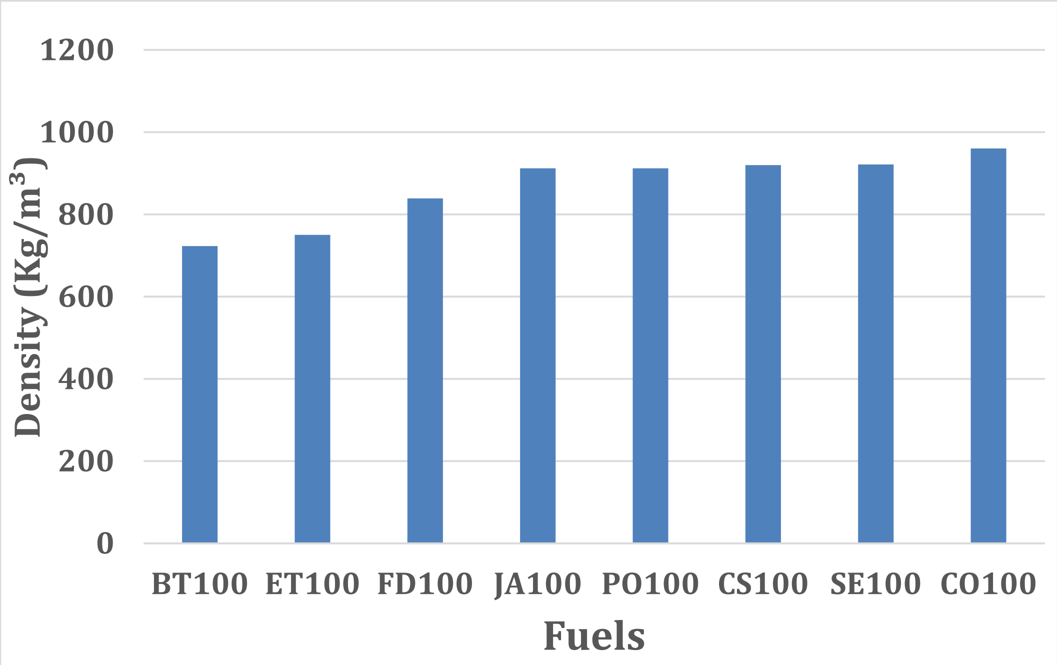


Figure 71: Density of FD100 with all pure samples.

The density of plant oils depends on their composition and origin. Pure plant oils, at 16 °C, show higher density values in comparison with FD and their blends with BT100 and ET100.

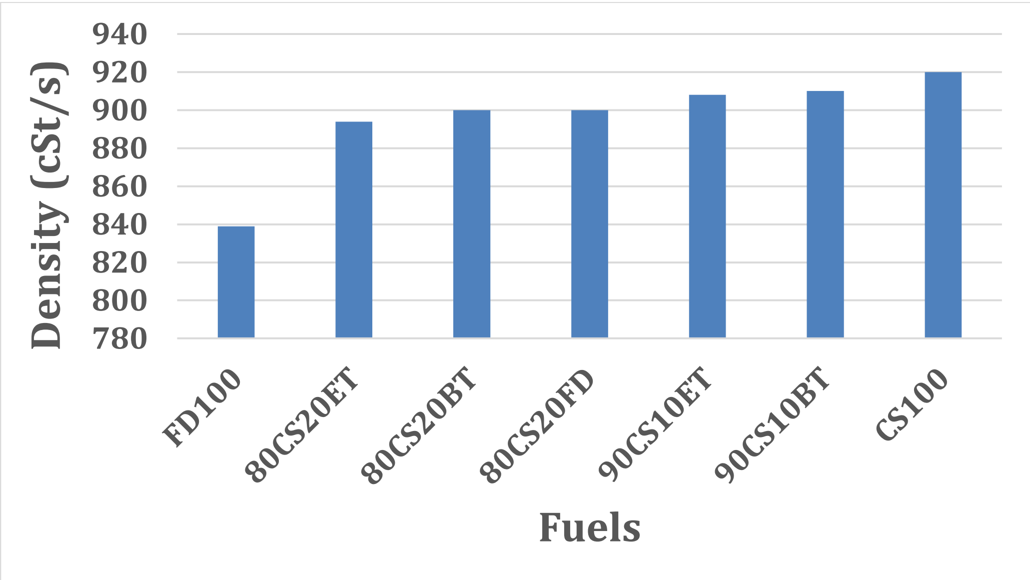


Figure 72: Density of FD100 and CS100 with its blends.

CO100 blends show density in the range 924 - 944 kg/m^3 while CS100 blends illustrate fewer density values in a range between 894 kg/m^3 and 910 kg/m^3. It can be observed, from the results, that CO100 has the highest density value of 960 kg/m^3 while 80CS20ET evidence the lowest density value of 894 kg/m^3 followed by 90CS10ET with a value of 908 kg/m^3 and 80CS20BT with a value of 900 kg/m^3.

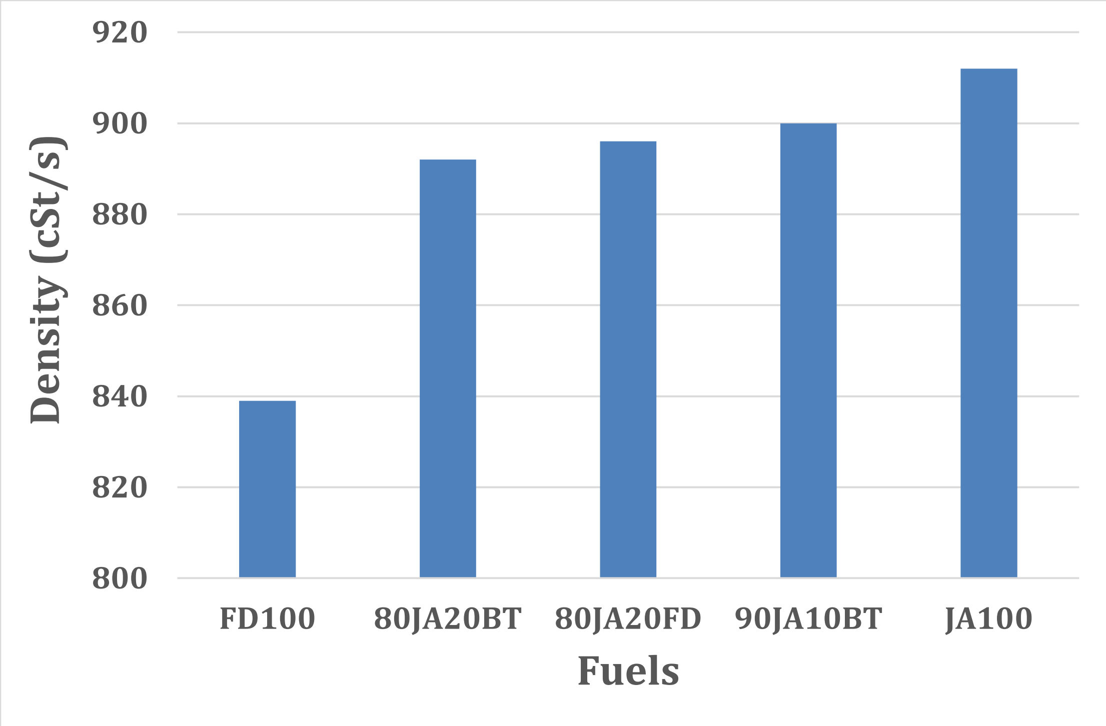


Figure 73: Density of FD100 and JA100 with its blends.

Regarding JA100 and its blends, density in the range 892-912 kg/m^3 ; comparing with FD100 is high (figure 73). Higher fuel density will require more pressure to pump. Furthermore, it will affect the mass fuel consumption rate.

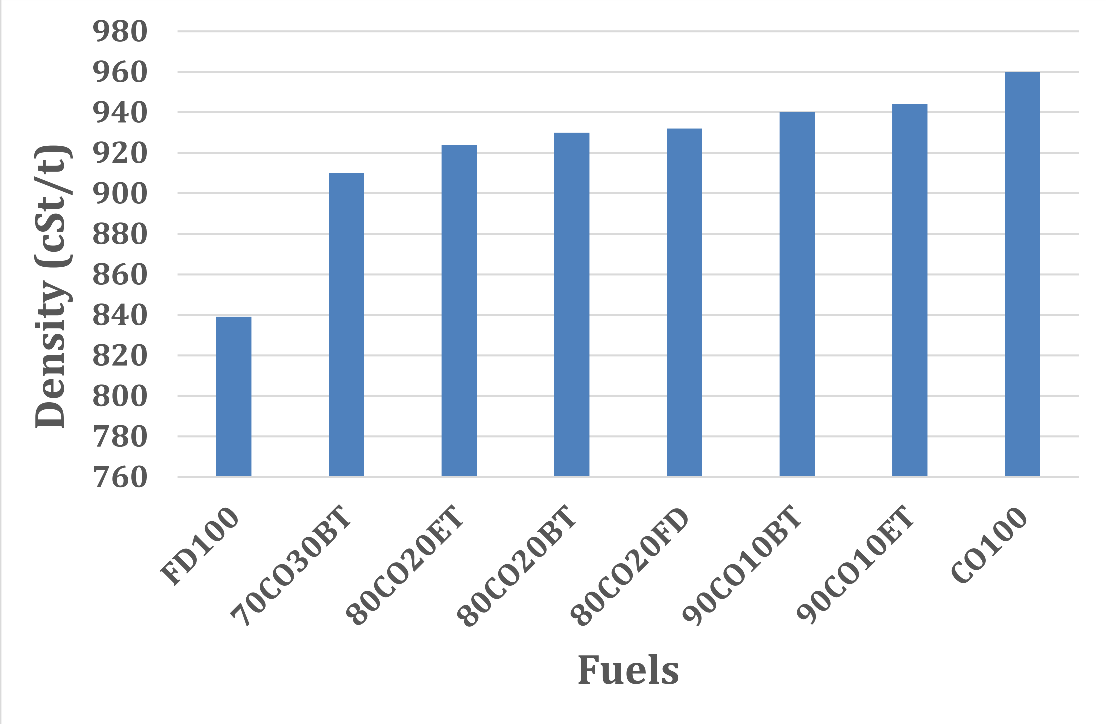


Figure 74: Density of FD100 and CO100 with its blends.

As figure 74 illustrates, CO100 and its blends show the highest density in comparison with all other fuels; blending with BT, ET and FD helped reducing it. In combination with HHV, high density could affect mass fuel consumption negatively.

5.5 Flashpoint measured values and analysis for all samples

Flashpoint of pure plant oil and its blends is very high comparing with FD100. The flash point of all fuels was shown in figure 75. CO100 shows the maximum value of 242 °C followed by SE100 with a value of 236 °C, 80PO20BT with a value of 220 °C and PO100 with a value of 232 °C. The only two fuels with lower flashpoint value that FD is ET100 and BT100 with values of 14°C and 36 °C respectively. That would not compromise the safety issues since both of them were used as blends with CO100 and CS100.

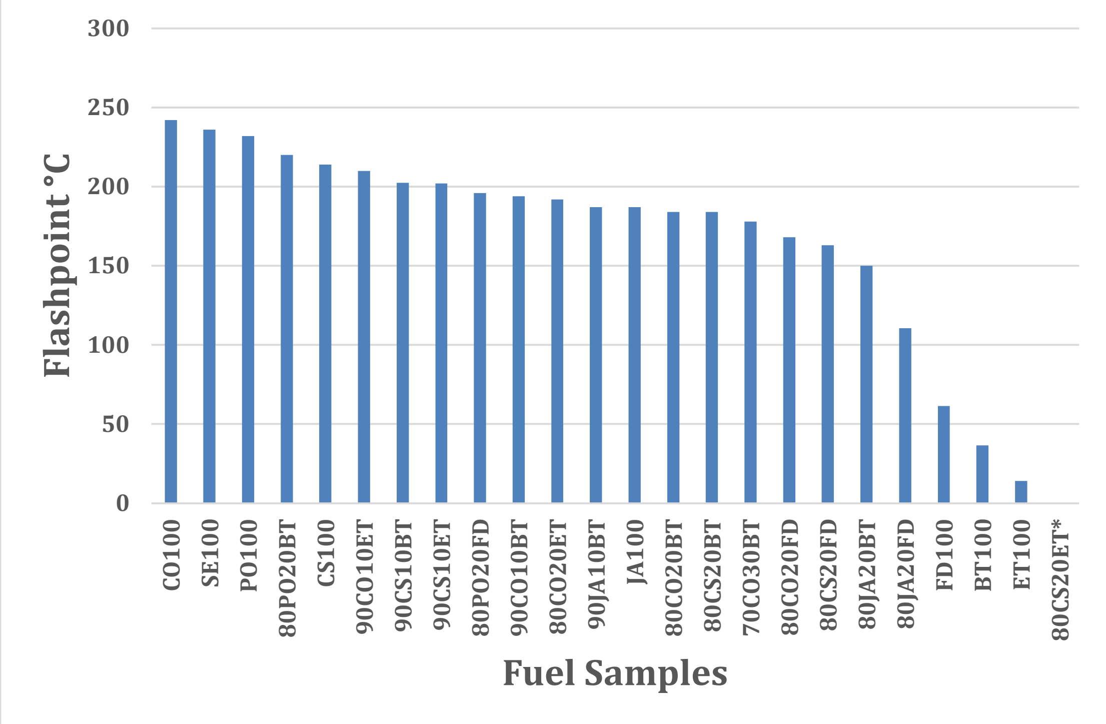


Figure 75: Flashpoint of pure plant oils -ASTM D3278.

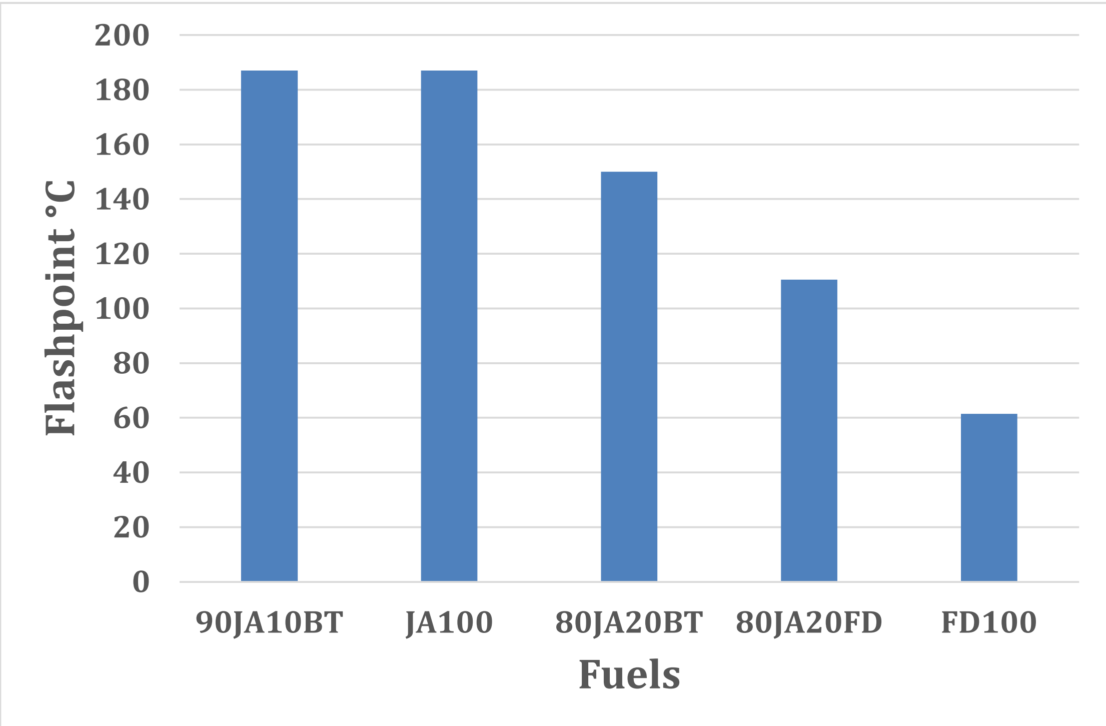


Figure 76: Flashpoint of JA100 and its blends.

As figures, 76, 77 and 78 show; JA100, CS100 and CO100 with their blends have a very high flashpoint comparing with FD100. These values demonstrate that they are safe regarding usage and storage.

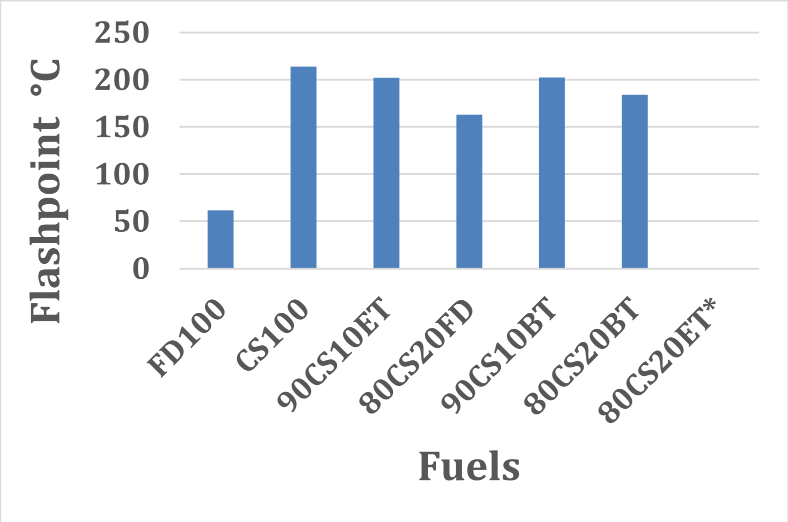


Figure 77: Flashpoint of CS100 and its blends.

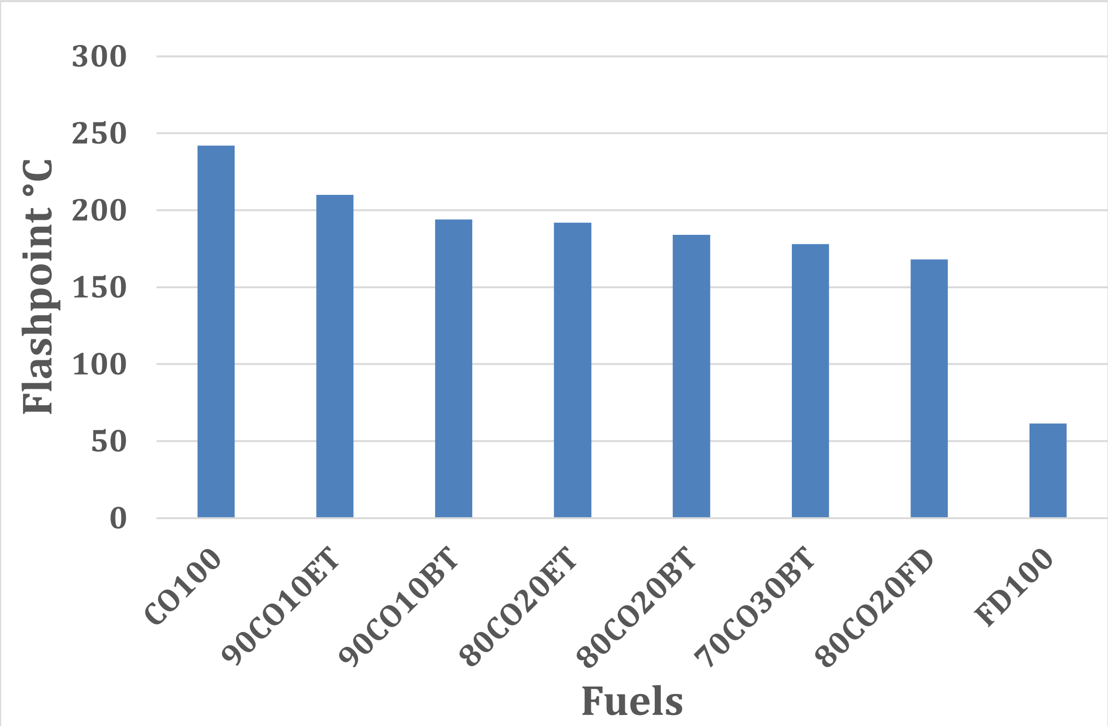


Figure 78: Flashpoint of CO100 and its blends.

5.6 Conclusions

In this chapter, the remarkable properties of plant oils evaluated for comparison with standard FD. This comparison is decisive for engine testing. In the first section fuels and fuels blends were prepared, and in the second section, HHV, Viscosity, Density, and Flashpoint were evaluated according to standard test methods and compared with FD.

Table 26: Properties of selected samples.

Samples	HHV (MJ/Kg)	Kinematic Viscosity cSt	Density (Kg/m^3)	Flashpoint (°C)
FD100	45.12	2.53	839	61.5
CS100	39.74	93	920	214
JA100	39.18	29.8	912	187
CO100	37.71	250	960	242
80CS20FD	40.41	17.96	900	163
80JA20FD	38.62	18.15	896	110.5
80CO20FD	38.49	76	932	168
80CS20BT	38.95	14	900	184
80JA20BT	38.66	15.54	900	150
80CO20BT	36.78	50	930	184

In terms HHV of pure plant oils, PO100 has a value of 40.13 MJ/kg followed by CS100 with a value of 39.74 MJ/kg, SE100 with a value of 39.47 and JA100 39.18 MJ/kg. While among the blends 90CS10BT has the closest value to FD with 39.95 MJ/kg followed by, 38.62 MJ/kg of 80CS20BT and 37.59 MJ/kg of 90CS10ET. All sample shows higher viscosity with a comparison to FD, but CS100 blends show low viscosity comparing with the other pure oils and blends (Table 26). The minimum viscosity of these blends is 80CS20ET with 10.82 cSt/s, but unfortunately, as it has been mentioned in section 8.2, it has miscibility problem. The second lower viscous blends are 80CS20BT with a value of 14.06 cSt/s followed by 90CS10ET with a value of 16.09.

CO100 blends show density in the range between 944 kg/m^3 and 924 kg/m^3 while CS100 blends illustrate fewer density values in a range between 894 kg/m^3 and 910 kg/m^3 . It can be observed, from the results, that CO100 has the highest density value of 960 kg/m^3 while 80CS20ET evidence the lowest density value of 894 kg/m^3 followed by 90CS10ET with a value of 908 kg/m^3 and 80CS20BT with a value of 900 kg/m^3 . Regarding Flashpoint, CO100 shows the highest value of 242 °C followed by SE100 with a value of 236 °C and CS100 with a value of 214 °C. The only two fuels with lower flashpoint value that FD is ET100 and BT100 with values of 13°C and 36.5 °C respectively. In general, all the pure plant oils and its blends have higher flashpoint than standards FD.

As a conclusion, CS100, JA100, and CO100 with BT100 and FD100 blends are the most suitable blends for engine testing. Viscosity is the mean concern; blending and the high temperature of Sudan could minimize its consequences on engines.

Chapter 6: Plant oils.' engine performance and exhaust emission results and discussion

6.1 Introduction

In an agricultural country like Sudan, the use of vegetable oils in IC engine has to be comprehensively examined. Sudan has an enormous production capacity of Cottonseed, Castor seed, and Jatropha Curcas seeds. This chapter will cover the result and discussion of engine performance and exhaust emission using JA100, CS100 and CO100 and its blends as a fuel.

6.2 Jatropha oil (JA100) and its blends

Jatropha plant has been introduced to Sudan soils recently after a pilot study was conducted; which showed the real potential of using its seed for biodiesel production.

6.2.1 Engine performance

Using JA100, 80JA20BT and 80JA20FD full engine power was attained; engine performance parameters were measured and equated with FD100. The brake and indicated power were compared (Figure 79); both powers, of all samples, were less than FD100; this due to high mass fuel consumption of all samples at all load; this could be attributed to the high density of all sample in comparison with FD100 (Table 26). JA100, 80JA20FD and 80JA20BT have 8.7%, 6.7% and 7.2% higher density than FD100, respectively. In addition to that, high density probably caused uneven combustion inside the cylinder; as a result, it drops the brake power.

Although that HHV of, JA100, 80JA20BT and 80JA20FD are less by 13.2%, 15%, and 11% respectively; indicated powers were only around 3.4% less than FD100 in all loads. This drop in indicated power could be attributed to high fuels density which compensates engine power. Regarding The Brake Specific Fuel Consumption (BSFC) as Figure 80 shows, the low HHV of all sample comparing to FD100 let engine consume more fuels to deliver same powers in various load. High fuel density (Table 26) let the differences in fuel consumption looks higher due to weight basis calculation rather that volume basis. At full engine load, BSFC of all samples was 18.4% greater than FD100 on a weight basis, while in low load it was 26.13% higher for 80JA20BT and 19.9% larger than FD100 for both JA100 and 80JA20FD. In low load, high density and viscosity of the samples could have delayed the start of combustion due to poor fuel injection, but in high load, the temperature (Figure 83) was high enough to minimize or eliminate this problem. Brake thermal efficiency for all samples was almost similar to FD100 (Figure 81) with some drops, in average 4.4% and 7% of high load, where the engine consume more fuels to compensate the slight power loss. Mechanical efficiency of all samples shows consistency with that of FD100 (Figure 82). The lubricity of samples minimized the friction power, but high density and viscosity required more energy loss due to poor atomization in the combustion chamber. These two, gaining and losing powers, over right one another and helped mechanical efficiency to be almost similar to FD100. The exhaust temperature of all samples was lower than FD100 by around 17% at low load whereas at high load were higher by 11% for 80JA20BT and by 15% for JA100 and 80JA20FD. This temperature difference can be attributed to the increase of compression ratio (Lambda), and it increased HC emissions as a result.

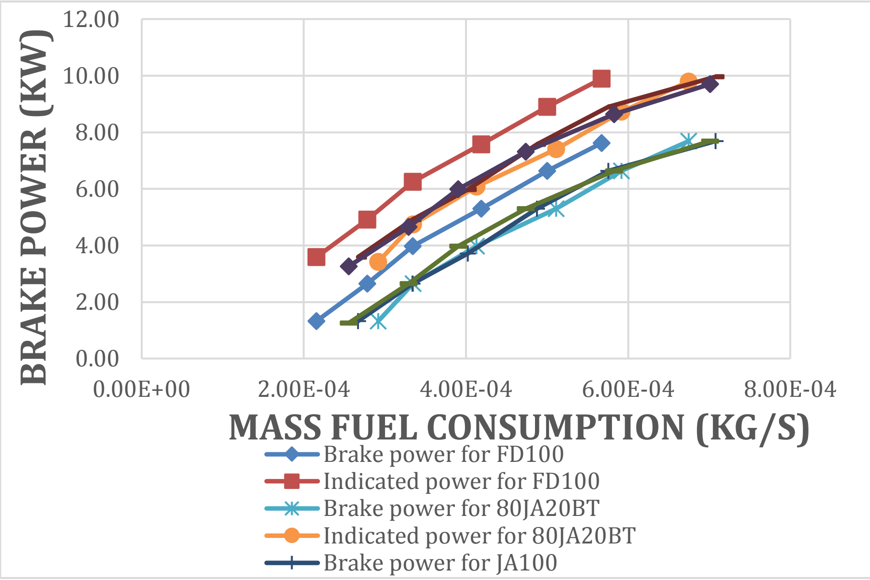


Figure 79: Brake and Indicated powers vs. Mass Fuel consumption of FD100 & JA100 and its blends.

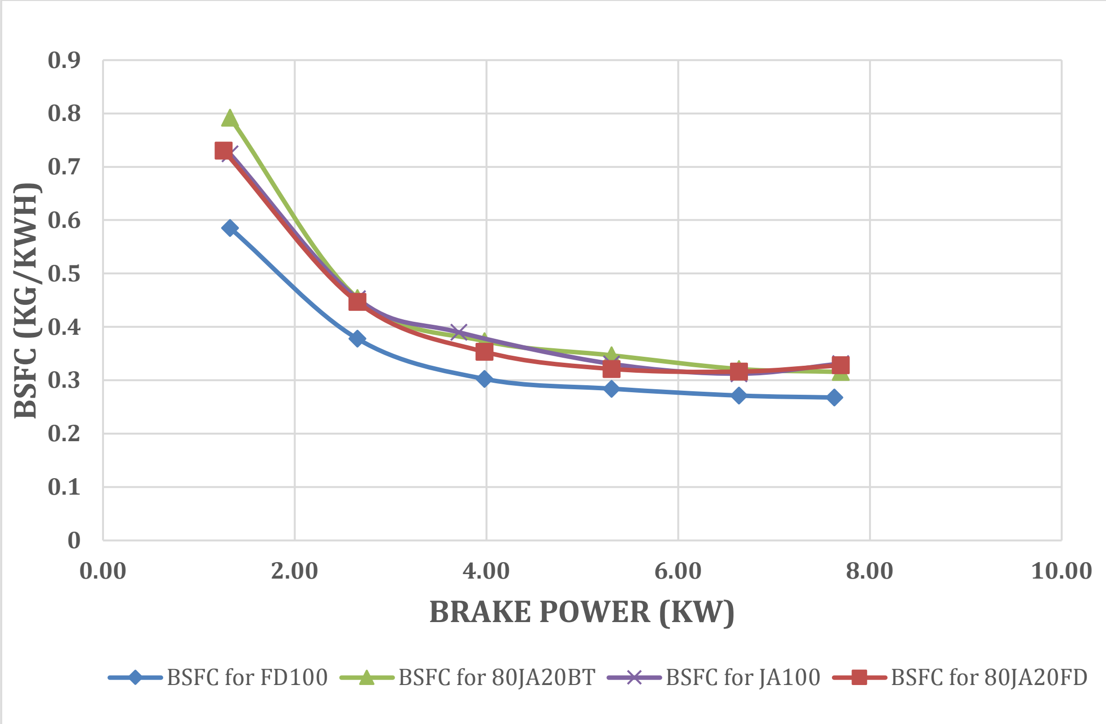


Figure 80: Brake Specific Fuel Consumption vs. load of FD100, JA100, and its blends.

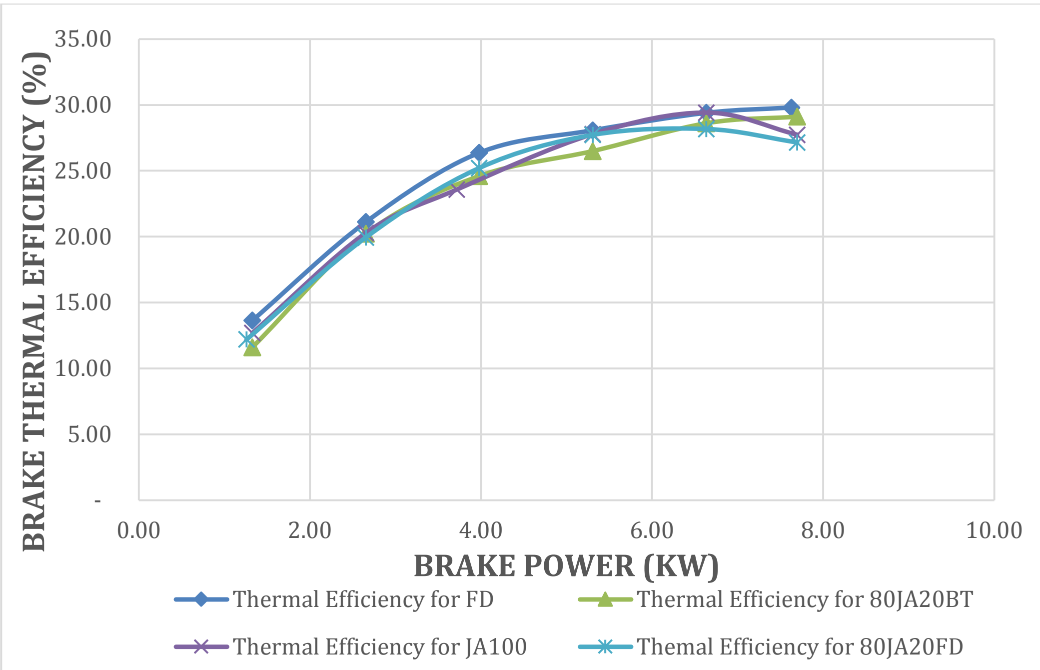


Figure 81: Brake Thermal Efficiency vs. load of JA100 and its blends.

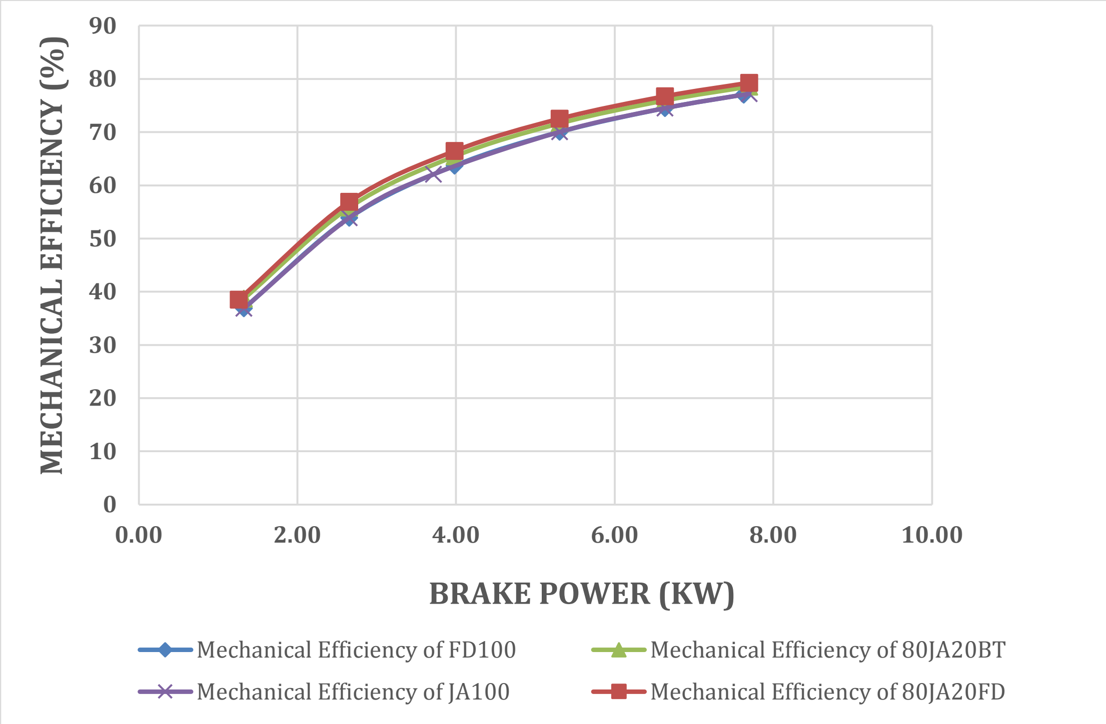


Figure 82: Mechanical Efficiency vs. load of FD100, JA100 and its blends.

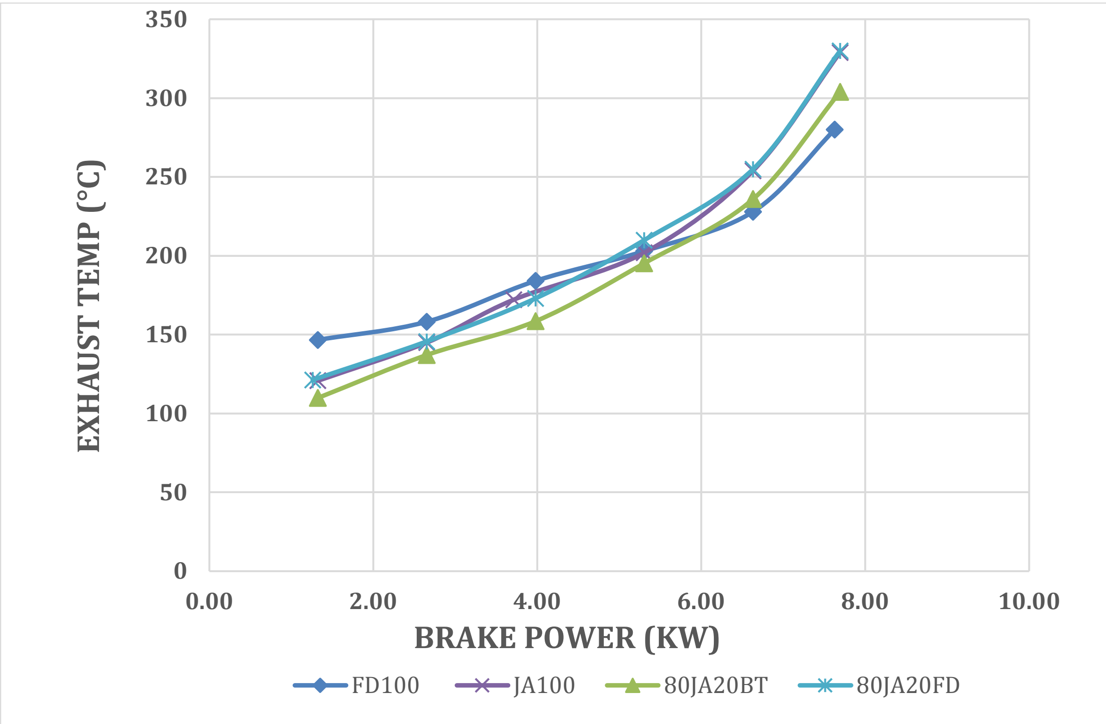


Figure 83: Exhaust temperature vs. load of FD100, JA100 and its blends.

6.2.2 Exhaust gas emissions

The Green House Gas (GHG) produced by JA100, 80JA20BT and 80JA20FD were measured and compared with FD100 emissions. As Figure 84 illustrates, Carbon Monoxide (CO) emissions of all sample were higher than that of FD100. At low load it were 76.5%, 74.2% advanced than FD100 for 80JA20BT, JA100 & 80JA20FD respectively; while in high load, 80JA20BT and JA100 & 80JA20FD CO emissions were dropped to 41.4%, 53% greater than FD100 respectively. High CO emissions of all samples could be attributed to the high oxygen content in all tested samples. Oxygen (O_2) emissions show decreasing tendency with the increase of load (Figure 85) but no big difference from FD100. Carbon Dioxide (CO_2) of all samples inclusive FD100 were taken increasing tendency following the increase of load with exceptional in maximum load which showed a higher increase, where 80JA20BT, JA100 & 80JA20FD have shown 15.4%, 18.6% increase on FD100. As it was explained earlier, these fuels have higher consumption at maximum load which in return caused higher CO_2 emissions.

From Figure 87 it can be seen that the hydrocarbon (HC) emissions of JA100, 80JA20BT and 80JA20FD whether similar or higher than FD100. 80JA20BT has similar HC emissions to FD100 of 5 ppm; this is due to the low combustion temperature of 80JA20BT in low load which was 33% lower than FD100. The low temperature could cause the air-fuel mixture not to combust as quick as the time of the power stroke. The other two fuels showed HC emissions of 2ppm at low load. These results could be attributed to the high temperature, relatively, comparing with 80JA20BT. During the other load, HC emission of all samples kept fluctuating but still higher that FD100 HC emissions; this fluctuating are due to the variable operating conditions due to the high density and viscosity which could have caused untidy injection. As Figure 88 shows, Lambda of all sample showed consistency with a lambda of FD100 except 80JA20BT which was around 5% higher than all other fuels in low load. This high values could be due to the methanol (oxygenators) which release oxygen at the time of combustion; this oxygen rise lambda (the air-fuel ratio). In medium and higher load lambda for all sample was low. Low Lambda at these load is desirable since high lambda could cause knocking due to the high temperature of the mixture which causes high cylinder pressure.

Nitrogen Oxides (NO_X) as Figure 89 illustrates, reduced for all sample comparing with FD100. In low and medium load NO_X reduction reached 30-32 % while in high load, reduction reached the range 5 – 13 %; this could be attributed to the combustion temperatures. In low load the combustion temperatures were low (Figure 83) hence NO_X emission was low but when it raised up the NO_X emissions increased. Regarding smoke, all samples showed low smoke production in comparison with FD100. In low load reduction of smoke, the level was 60% while in high load it was 84% for 80JA20BT and 96% for both JA100 and 80JA20FD. This low production level was attributed to the high oxygen in all blend which helped proper combustion of all fuels.

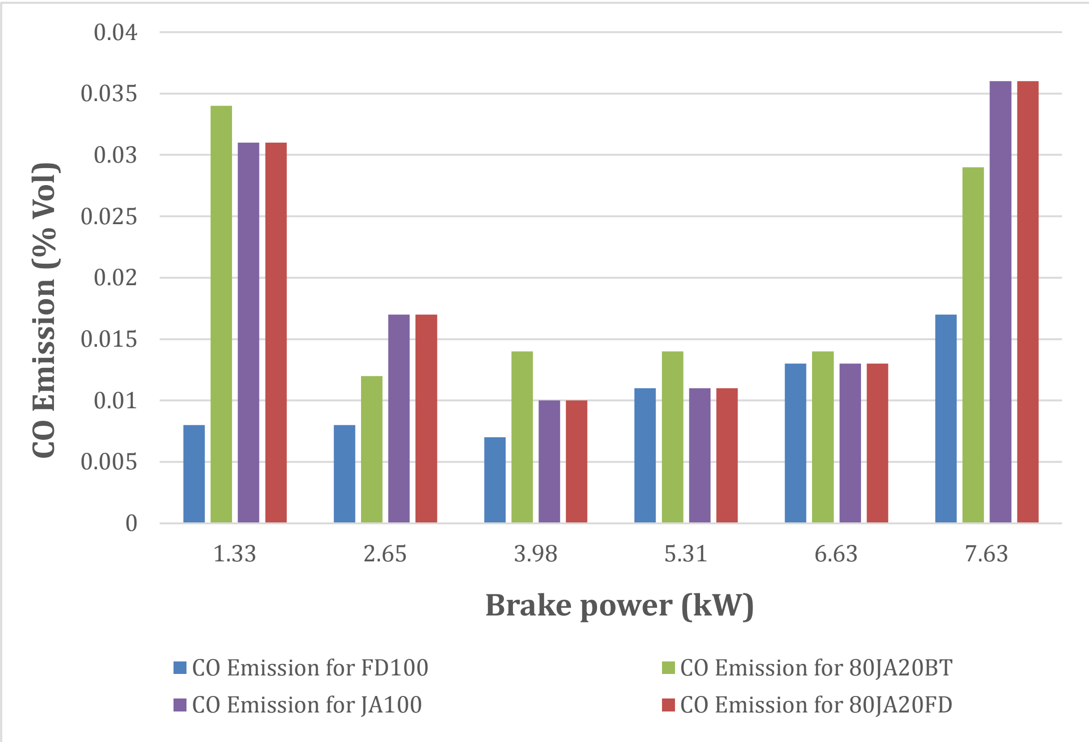


Figure 84: CO emission vs. load of FD100, JA100 and its blends.

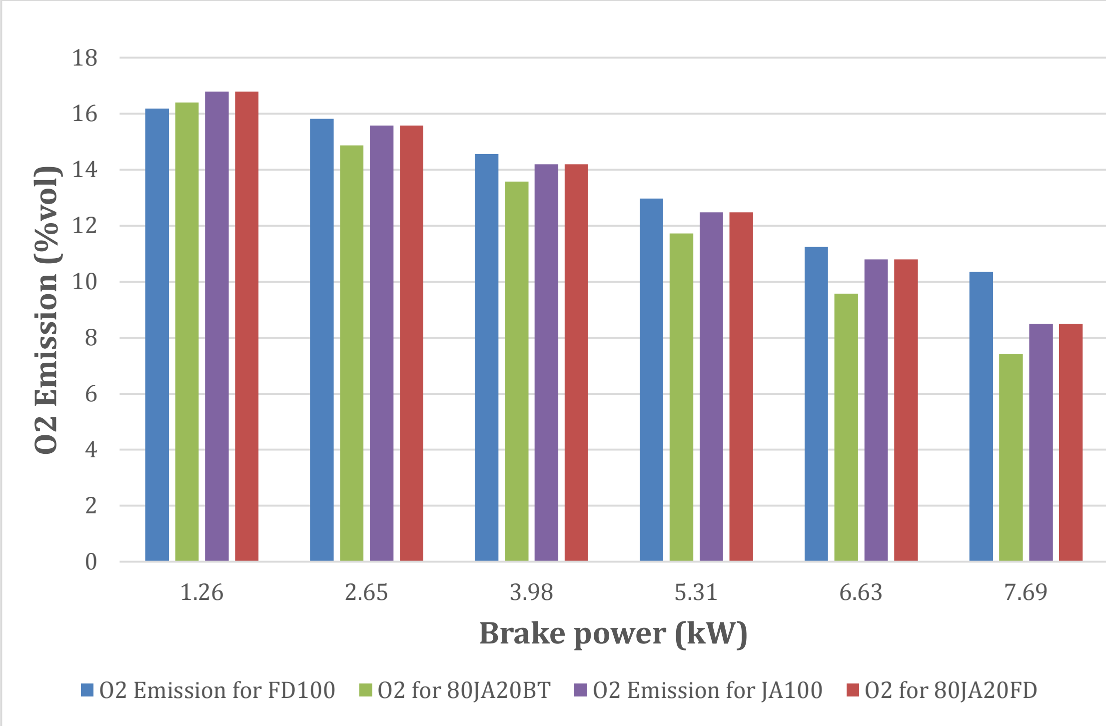


Figure 85: O_2 emission vs. load of FD100, JA100 and its blends.

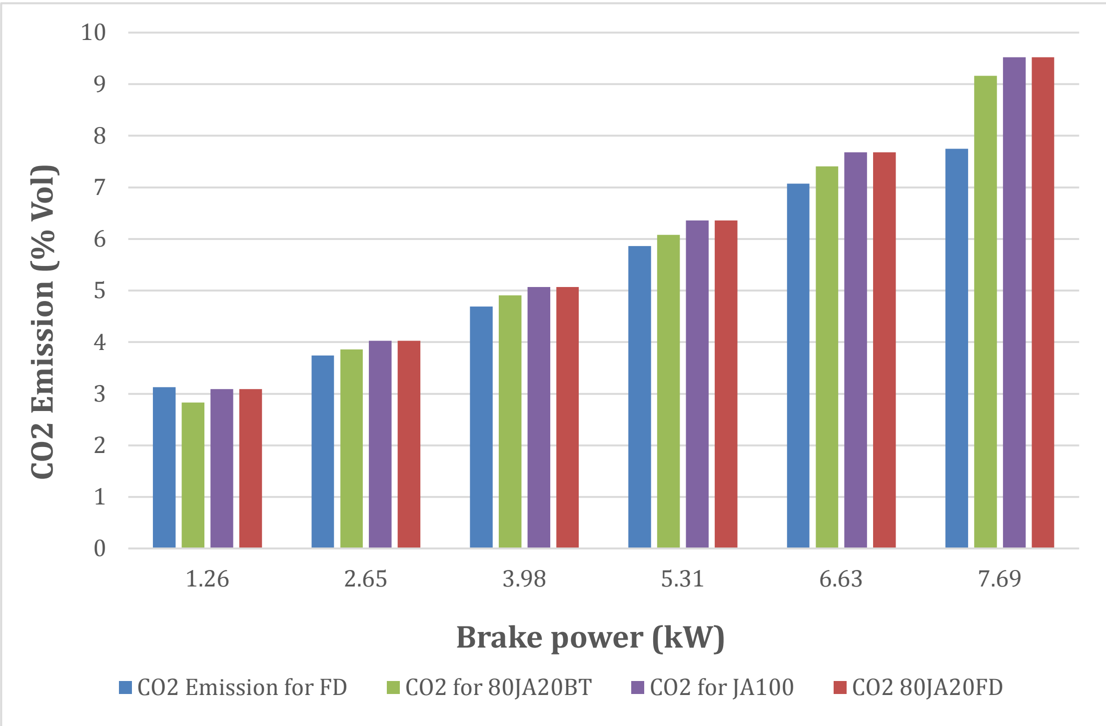


Figure 86: CO_2 Emission vs. load of FD100, JA100 and its blends.

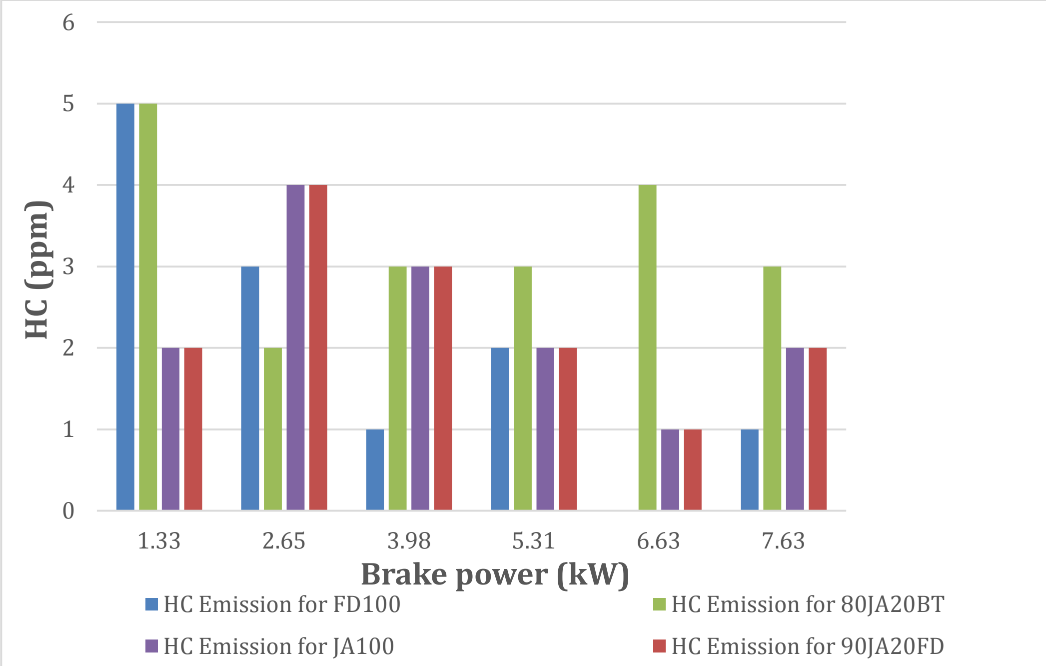


Figure 87: HC emission vs. load of FD100, JA100 and its blends.

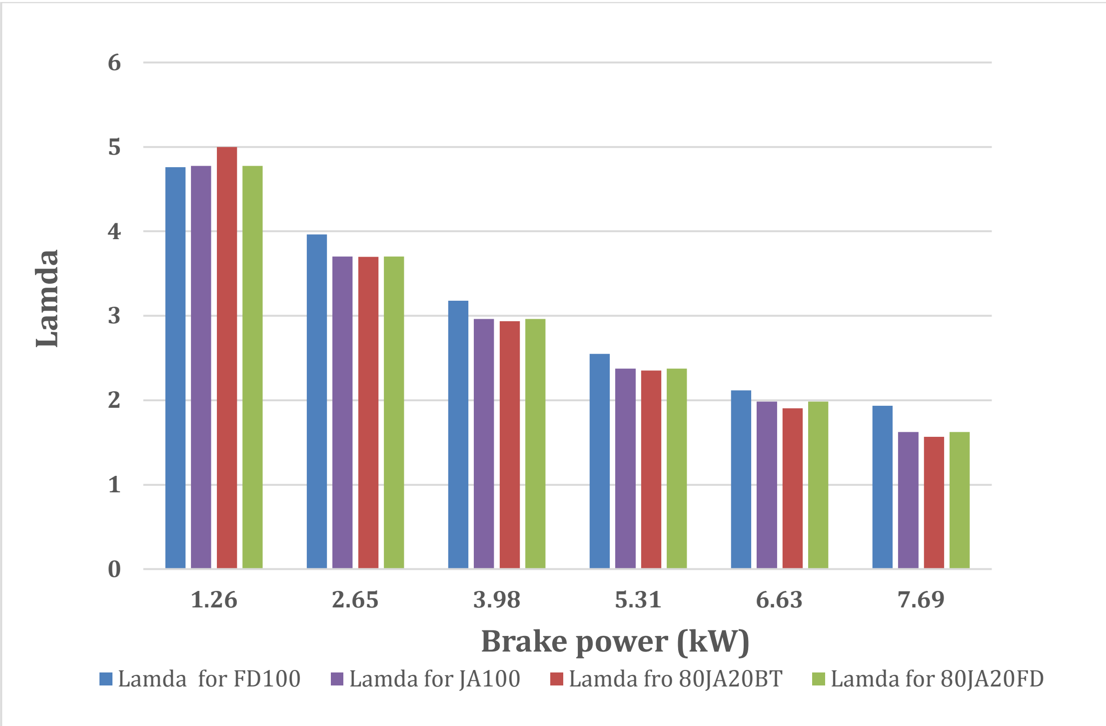


Figure 88: Lambda vs. load of FD100, JA100, and its blends.

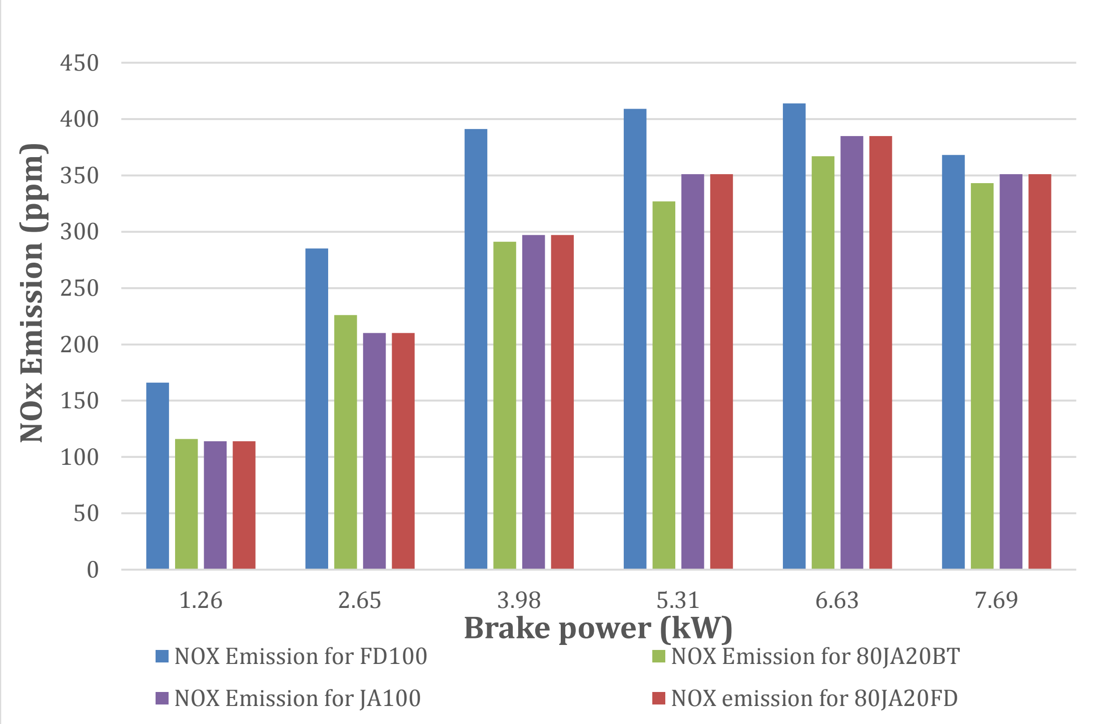


Figure 89: NO_X emission vs. load of FD100, JA100 and its blends.

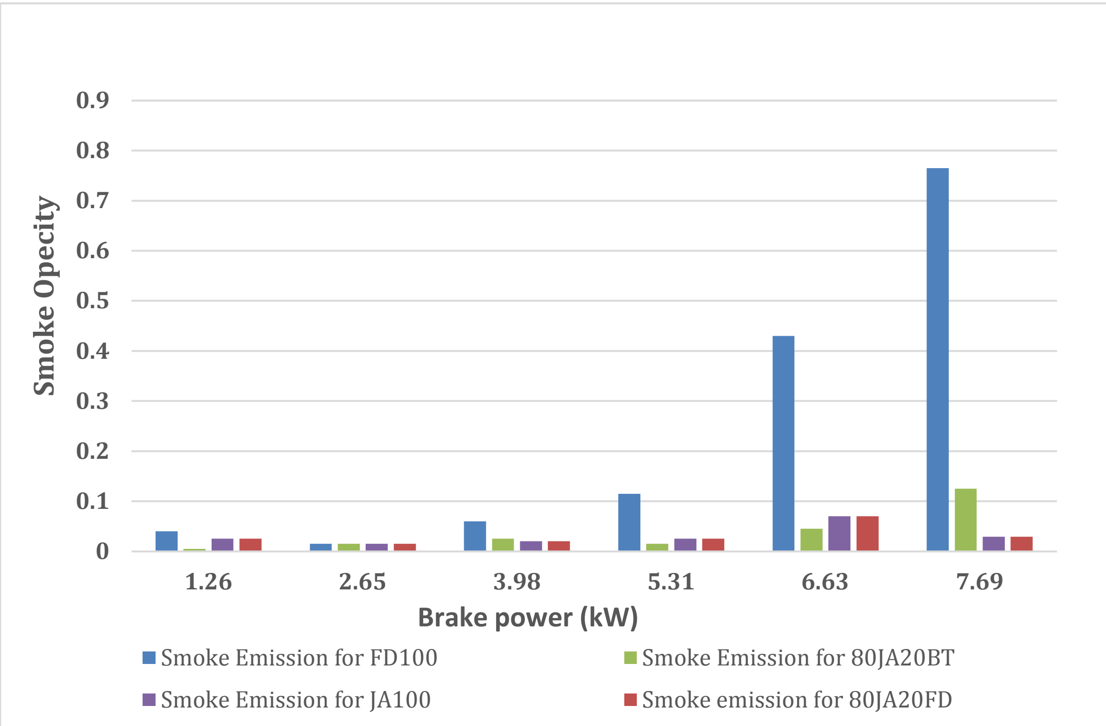


Figure 90: Smoke emission vs. load of FD100, JA100 and its blends.

6.3 Cottonseed oil (CS100) and its blends

Cottonseed, comparing to other oilseeds, is not grown exclusively for the production of oil. This fact let cottonseed considered secondary production. In 2014 the cotton production area was around 65K hectares. According to the Food and Agriculture Organisation (FAO), Sudan exported more than 21 ton of cottonseed in 2013; this could extract around 2.52 ton of oil annually.

6.3.1 Engine performance

Consuming CS100, 80CS20BT and 80CS20FD full engine power was attained; engine performance parameters were measured and equated with FD100. The brake and indicated power were compared (Figure 91); both powers, of all samples, were less than FD100; this due to high mass fuel consumption of all samples at all load; this could be attributed to the high density of all sample in comparison with FD100 (Table 26).

CS100, 80CS20FD and 80CS20BT have 9%, 7.2% and 7.2% higher density than FD100, respectively. In addition to that, high density probably caused uneven combustion inside the cylinder. As a result, it drops the brake power.

Although that HHV of, CS100, 80CS20BT and 80CS20FD are less by 13.54%, 16%, and 11.6% respectively; indicated powers were only around 4.3% less than FD100 in all load; this could be attributed to high fuels density which compensates engine power. Regarding The Brake Specific Fuel Consumption (BSFC) as Figure 92 shows, the low HHV of all sample comparing to FD100 let engine consume more fuels to deliver same powers in various load. High fuel density (Table 26) let the differences in fuel consumption looks higher due to weight basis calculation rather that volume basis.

At full engine load, BSFC of all samples was 16% greater than FD100 on a weight basis, while in low load it was 19% higher for 80JA20BT and 13.21% larger than FD100 for both JA100 and 80JA20FD. In low load, high density and viscosity of the samples could have delayed the start of combustion due to poor fuel injection, but in high load, the temperature (Figure 95) was high enough to minimize or eliminate this problem. Brake thermal efficiency for all samples was almost similar to FD100 (Figure 93) with some drops, in average 5.4% and 6.7% of high load, where the engine consume more fuels to compensate the slight power loss. Mechanical efficiency of CS100 showed consistency with that of FD100, while 80CS20FD and 80CS20BT showed 9% and 15% higher than FD100 (Figure 94). The lubricity of samples minimized the friction power, but high density and viscosity required more energy loss due to poor atomization in the combustion chamber. These two, gaining and losing powers, over right one another and helped mechanical efficiency to be almost similar to FD100. The exhaust temperature (Figure 95) of 80CS20BT, CS100 and 80FD20BT were lower than FD100 by around 11% and 22%, 22%, respectively, at low load whereas at high load were higher by 12% for 80CS20BT and by 13% for CS100 and 80CS20FD. This related to the increase of Lambda (compression ratio) as Figure 100 showed and as a result, it increased HC emissions as well (Figure 99).

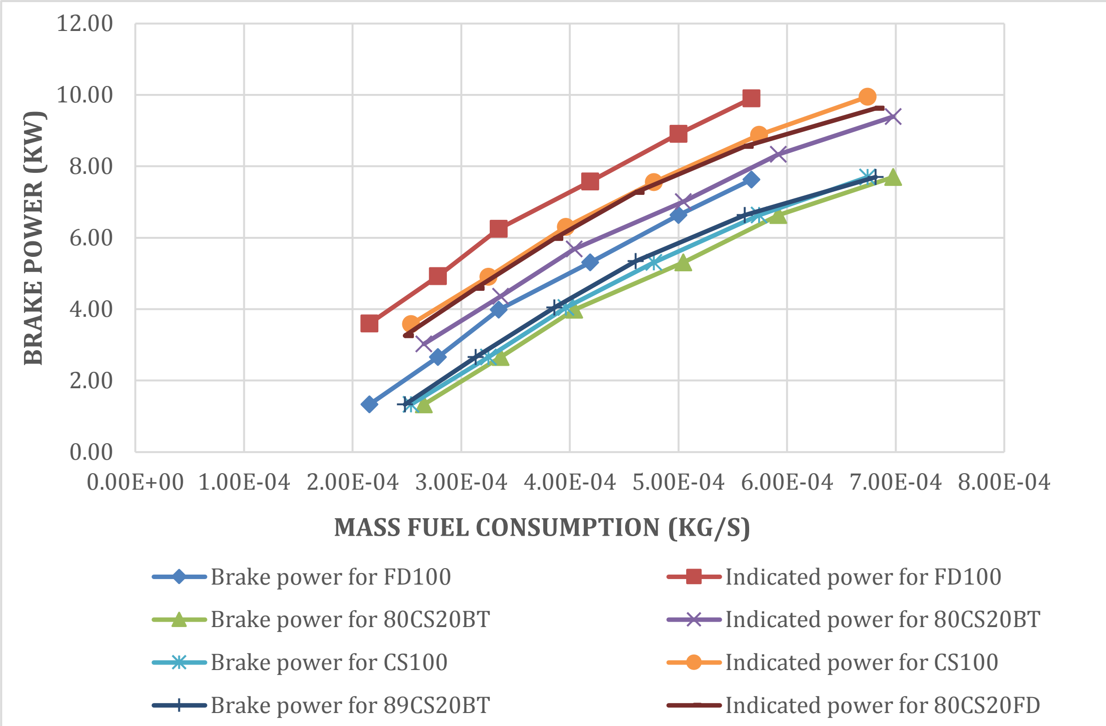


Figure 91*:* Brake and Indicated powers vs. Mass Fuel consumption of FD100 & CS100 and its blends.

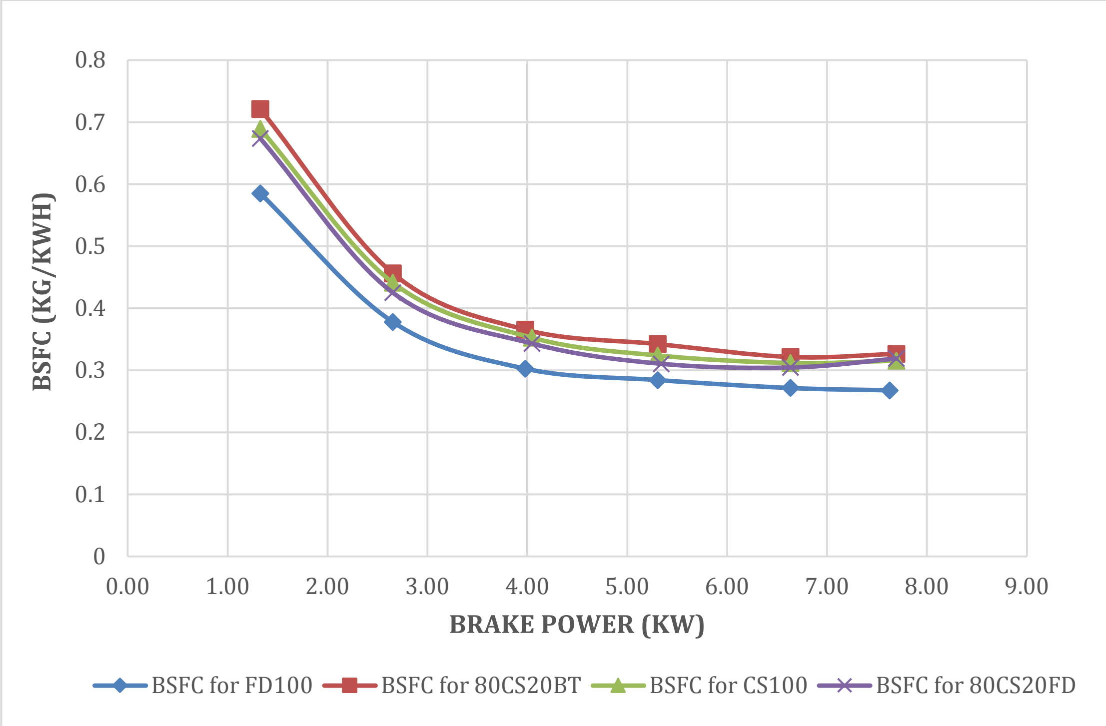


Figure 92: Brake Specific Fuel Consumption vs. load of FD100, CS100, and its blends.

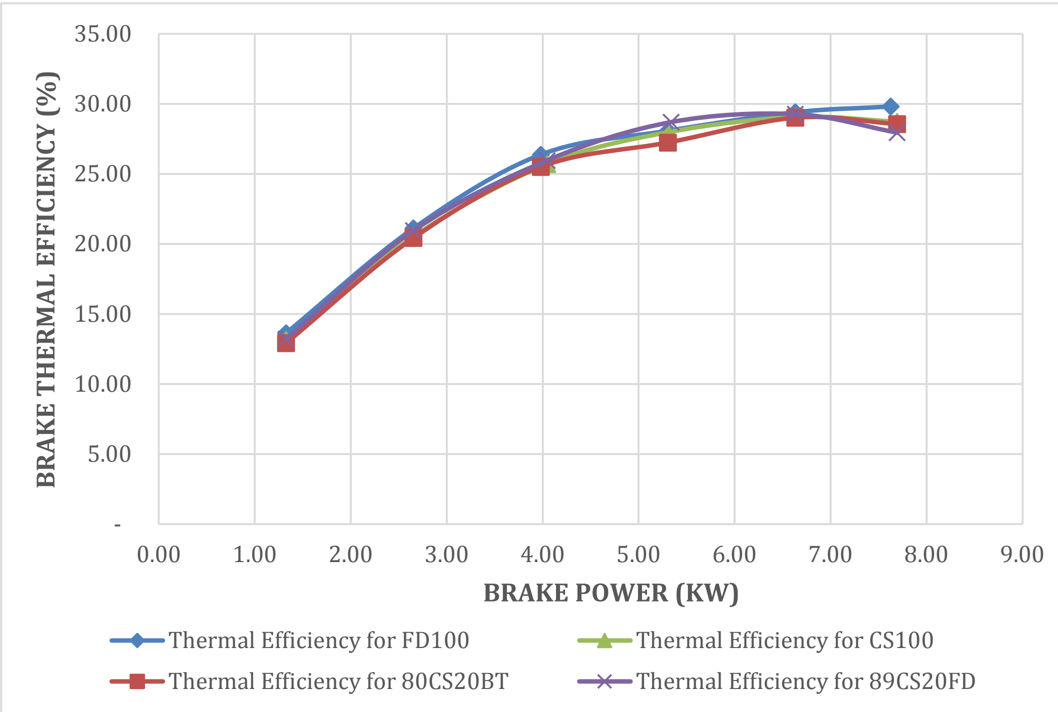


Figure 93: Brake Thermal Efficiency vs. load of CS100 and its blends.

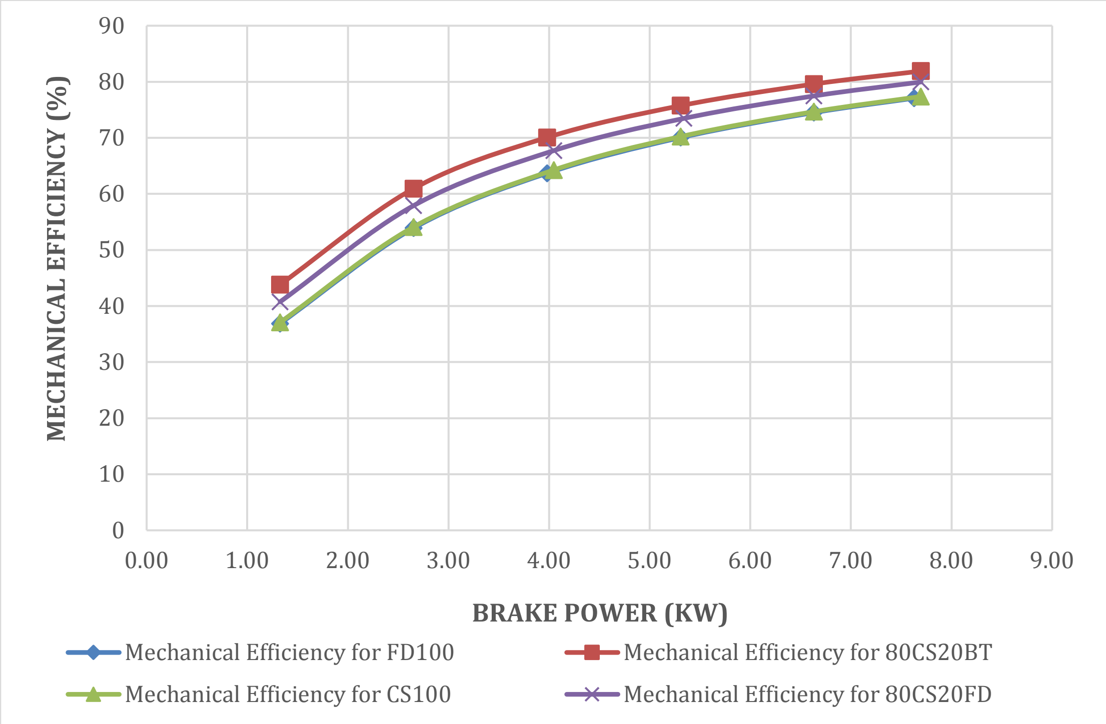


Figure 94: Mechanical Efficiency vs. load of FD100, CS100 and its blends.

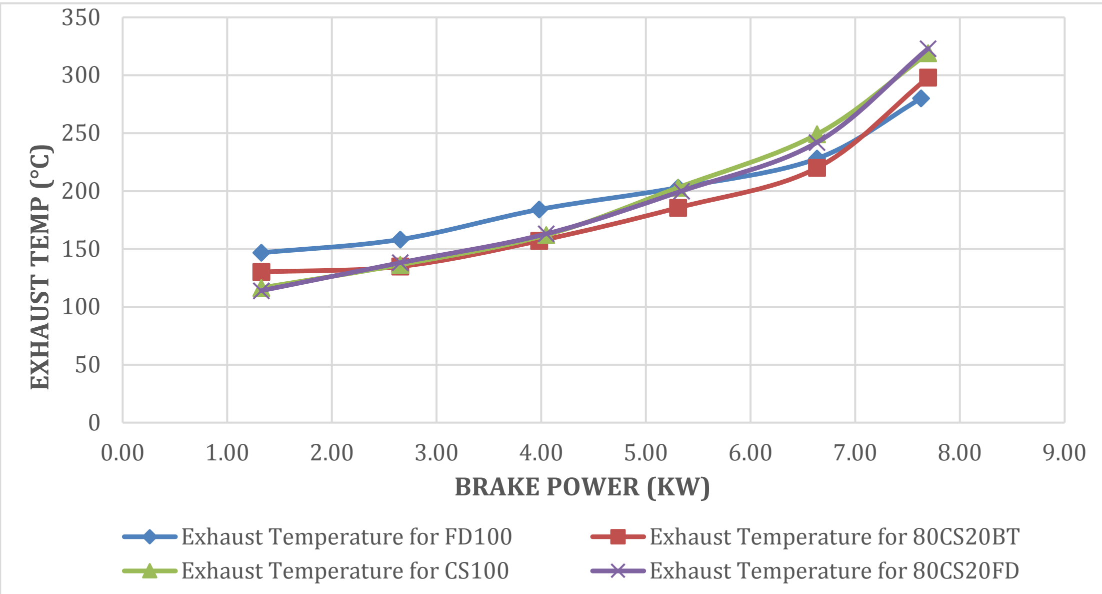


Figure 95: Exhaust temperature vs. load of FD100, CS100 and its blends.

6.3.2 Exhaust gas emissions

The Green House Gas (GHG) produced by 80CS20BT and 80CS20FD were measured and compared with FD100 emissions. As Figure 96 illustrates, Carbon Monoxide (CO) emissions of all sample were higher than that of FD100. At low load it were 64.6%, 33% superior than FD100 for 80CS20FD and CS100, respectively; in contrast, 80CS20BT showed reduction of 14%; while in high load, 80JA20BT showed high increase with 35% , followed by CS100 with 23%. 80JA20FD showed the lowest increase in 6% CO emission. High CO emissions of all samples could be attributed to the high oxygen content in all tested samples. Oxygen (O_2) emissions show decreasing tendency with the increase of load (Figure 97) but no big difference from FD100; this attributed to the high compression ratio (high lambda) due to the amount of Oxygen in the fuels. Carbon Dioxide (CO_2) of all samples inclusive FD100 were taken increasing tendency following the increase of load with exceptional in maximum load, the increase was higher, where 80CS20BT, JA100 & 80JA20FD have shown 15.4%, 18.6% increase on FD100. As it was explained earlier, these fuels have higher consumption at maximum load which in return caused higher CO_2 emissions.

From Figure 99 it can be seen that the hydrocarbon (HC) emissions of CS100, 80CS20BT and 80CS20FD whether similar or advanced than FD100. 80CS20BT has similar HC emissions to FD100 of 5 ppm; this is due to the low combustion temperature of 80CS20BT in low load which was 11% lower than FD100. The low temperature could cause the air-fuel mixture not to combust as quick as the time of the power stroke permit. CS100 and 80CS20FD showed HC emissions of 2ppm and 3 ppm respectively, at low load; this could be attributed to the high temperature, relatively, comparing with 80CS20BT. During the other load, HC emission of all sample kept fluctuating but still higher that FD100 HC emissions; this is due to the changing operating conditions due to the high density and viscosity which could have caused untidy injection. As Figure 88 shows, Lambda of all sample showed consistency with a lambda of FD100. Except for CS100 which was around 4% higher than FD100 in low load; this could be due to the Oxygen content in the fuel which releases oxygen at the time of combustion; this oxygen rise lambda (the air-fuel ratio). In medium and higher load lambda for all sample was low. Low Lambda at these load is desirable since high lambda could cause knocking due to the high temperature of the mixture which causes high cylinder pressure.

Nitrogen Oxides (NO_X) as Figure 101 illustrates, reduced for all sample comparing with FD100. In low and medium load NO_X reduction reached 19% while in high load reduction reached the range 5 – 7 %; this attributed to the combustion temperatures. In low load the combustion temperatures were low (Figure 95) hence NO_X emission was low but when it raised up the NO_X

emissions increased. Regarding smoke, all samples showed low smoke production in comparison with FD100. In low load reduction of smoke, the level was more than 50% while in high load it was in the range 62–91%. This low production level attributed to the high oxygen in all blend which helped proper combustion of all fuels.

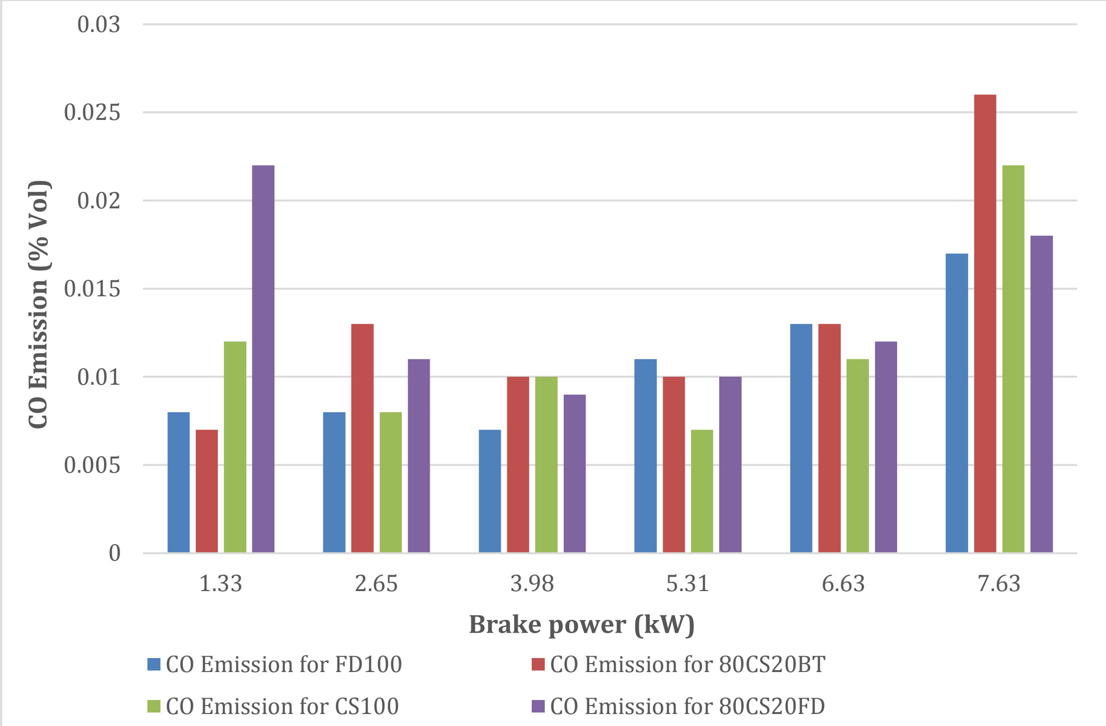


Figure 96: CO emission vs. load of FD100, CS100 and its blends.

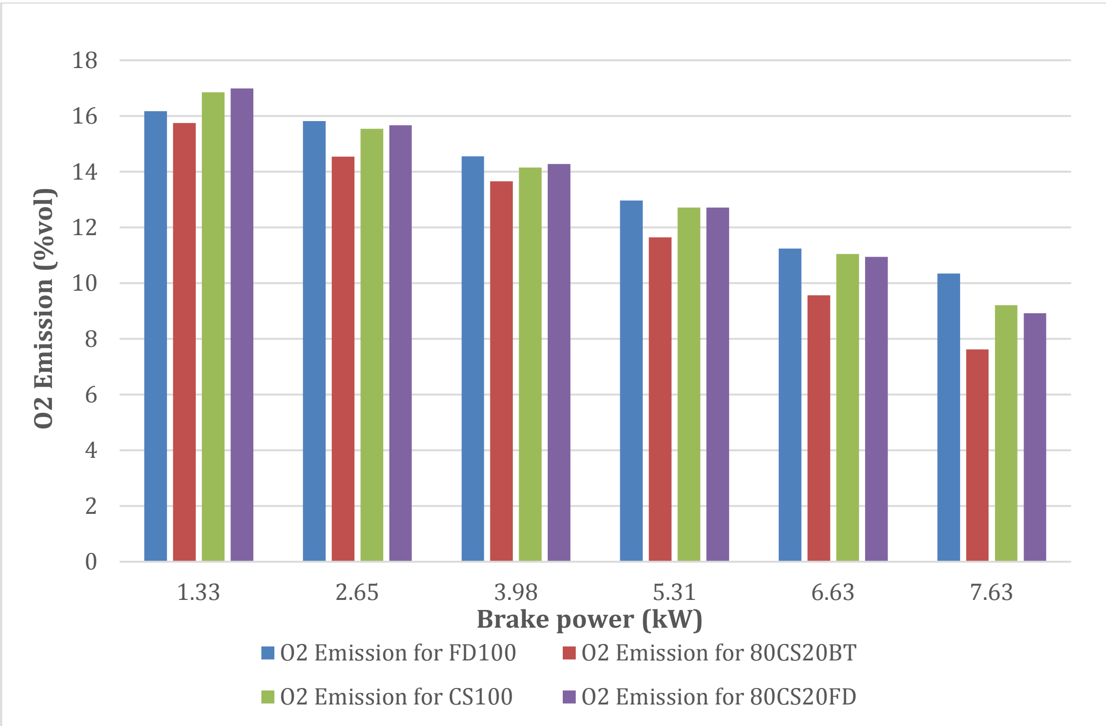


Figure 97: O_2 emission vs. load of FD100, CS100 and its blends.

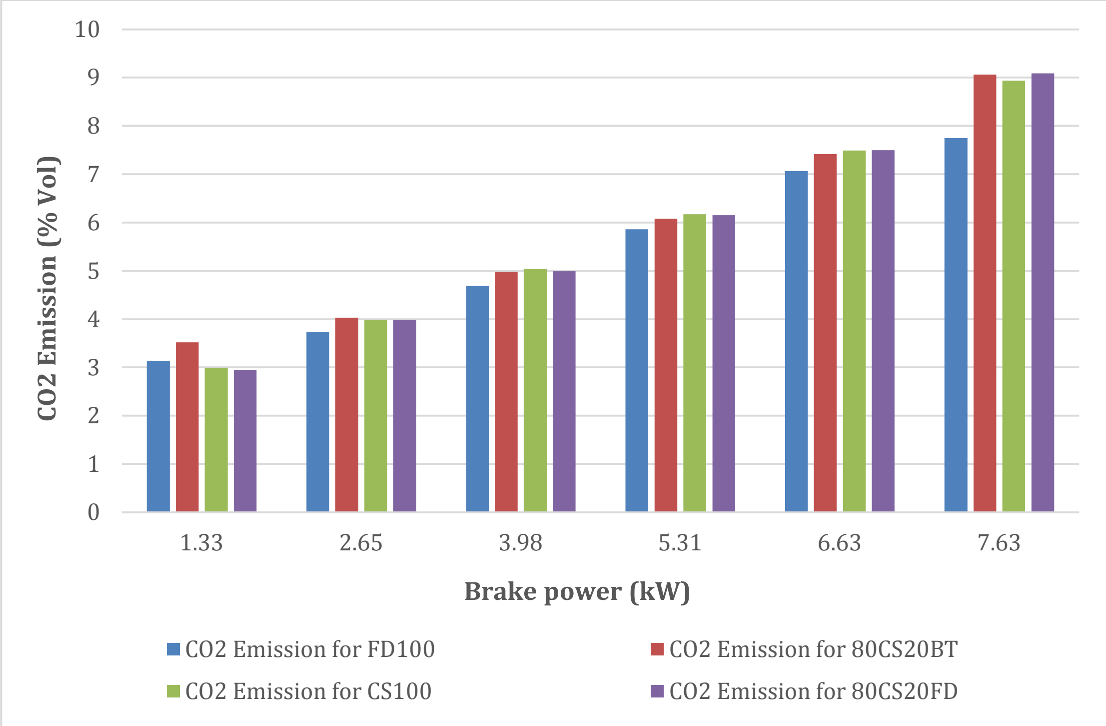


Figure 98: CO_2 Emission vs. load of FD100, CS100 and its blends.

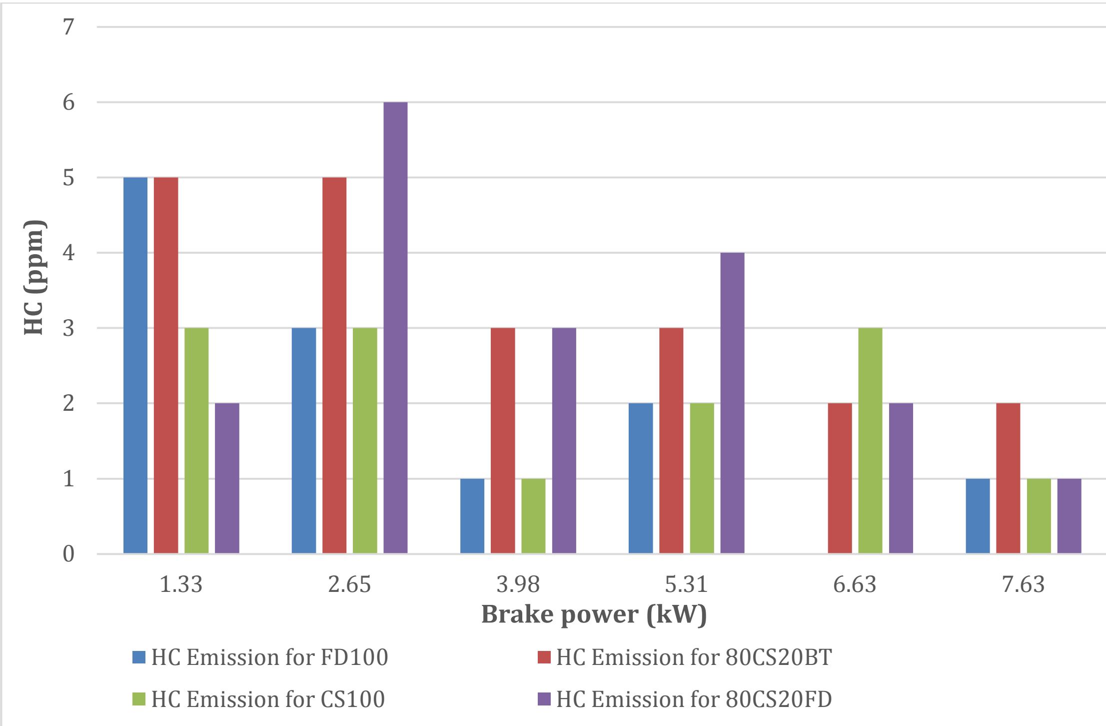


Figure 99: HC emission vs. load of FD100, CS100 and its blends.

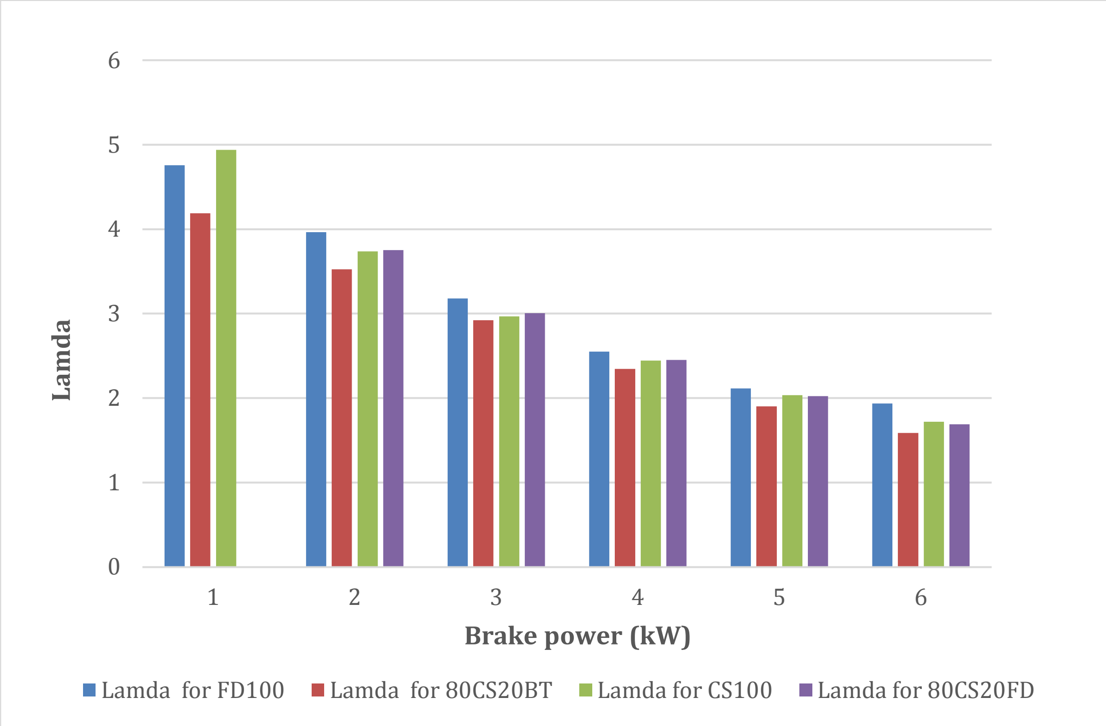


Figure 100: Lambda vs. load of FD100, CS100 and its blends.

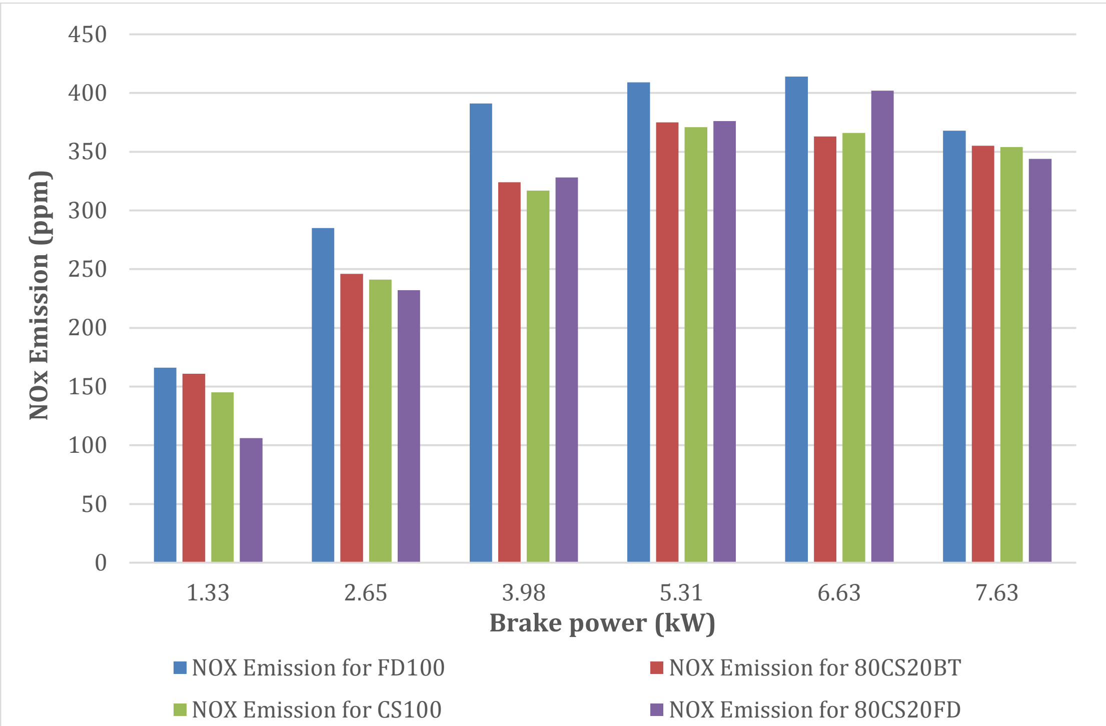


Figure 101: NO_X emission vs. load of FD100, CS100 and its blends.

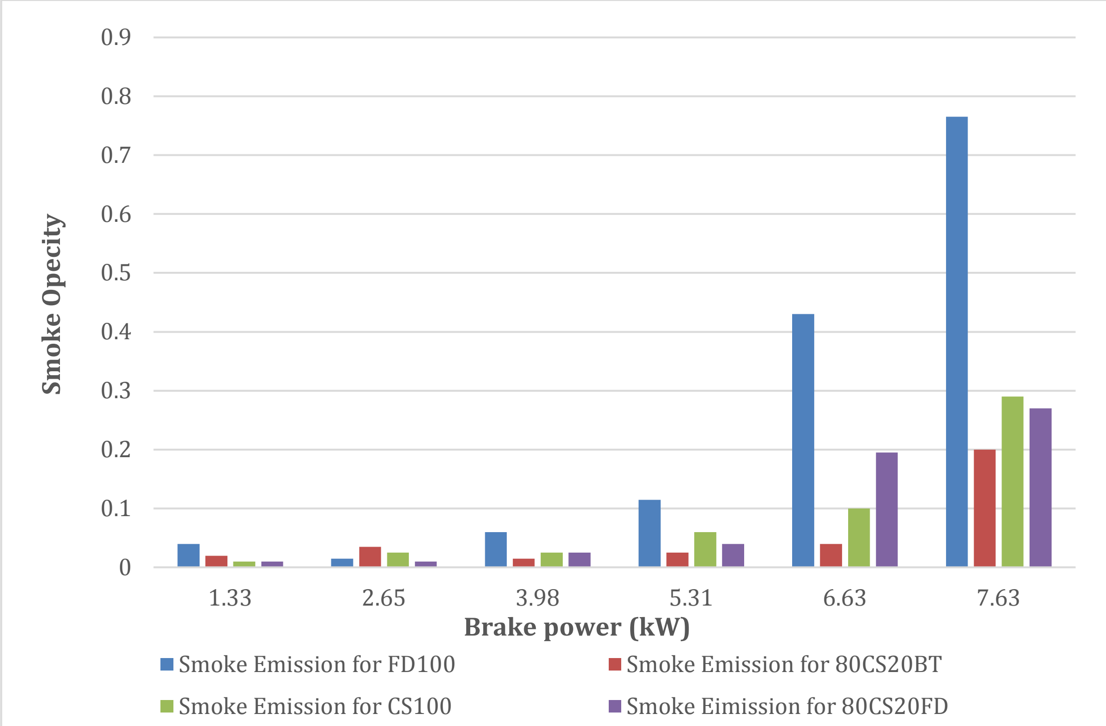


Figure 102: Smoke emission vs. load of FD100, CS100 and its blends.

6.4 Castor oil (CO100) and its blends

The area harvested for castor oil seed in 1975 was around 19 thousands hectare which is estimated to be around 38,000 ton of oil. Together with cottonseed, castor oil's beans had exceeded 50% of Sudan GDP at that time. In 1998 castor beans harvested area dropped to only 2000 ha which is around 4,000 ton.

6.4.1 Engine performance

Utilizing 80CO20BT and 80CO20FD with full engine power was attained; engine performance parameters were measured and equated with FD100. The brake and indicated power were compared (Figure 103); both powers, of all samples, were less than FD100; this due to high mass fuel consumption of both samples at all load; this attributed to the high density of both sample in comparison with FD100 (Table 26).

80CO20FD and 80CO20BT have both around 10% higher density than FD100. In addition to that, high density probably caused uneven combustion inside the cylinder. As a result, it drops the brake power.

Although that HHV of 80CO20FD and 80CO20BT are less by around 23% and 17% respectively; indicated powers were around 28% less than FD100 in all load. At low load 80CO20FD was less by around 43%; this attributed to high fuels density which compensates engine power, from one side and the difference in viscosity from the other side; which was in favor of 80CO20BT with 52% less viscosity than 80CO20FD. Regarding The Brake Specific Fuel Consumption (BSFC) as Figure 104 shows, the low HHV of both samples comparing to FD100 let engine consume more fuels to deliver same powers in various load. High fuel density (Table 28) let the differences in fuel consumption looks higher due to weight basis calculation somewhat than volume basis.

At full engine load, BSFC of both samples were 21% sophisticated than FD100 on a weight basis, while in low load it was 25% higher for 80CO20FD and 21% upper than FD100 for 80CO20BT. In low load, high density and viscosity of the samples could have delayed the start of combustion due to poor fuel injection, but in high load, the temperature (Figure 107) was high enough to minimize or eliminate this problem. Brake thermal efficiency for both samples was almost similar to FD100 (Figure 105) with some drops, in average load 80CO20FD and 80CO20BT drop by 3% and 13% respectively; while in high load, it decreased by 8% for both fuels. These drops ensue because the engine consumes more fuels to compensate the slight power loss. Mechanical efficiency of 80CO20FD and 80CO20BT showed consistency with that of FD100 (Figure 106). The lubricity of samples minimized the friction power, but high density and viscosity required more energy loss due to poor atomization in the combustion chamber. These two, gaining and losing powers, over right one another and helped mechanical efficiency to be almost similar to FD100; nevertheless, 80CO20BT showed a slight drop in all load which is the result of viscosity difference. The exhaust temperature (Figure 107) of 80CO20BT and 80FD20FD were lower than FD100 by around 26%, at low load whereas at high load it was higher by 10% for both samples. This related to the increase of Lambda (compression ratio) as Figure 112 showed and as a result, it increased HC emissions as well. High viscosities of both samples have resulted in reduced combustion characteristics.

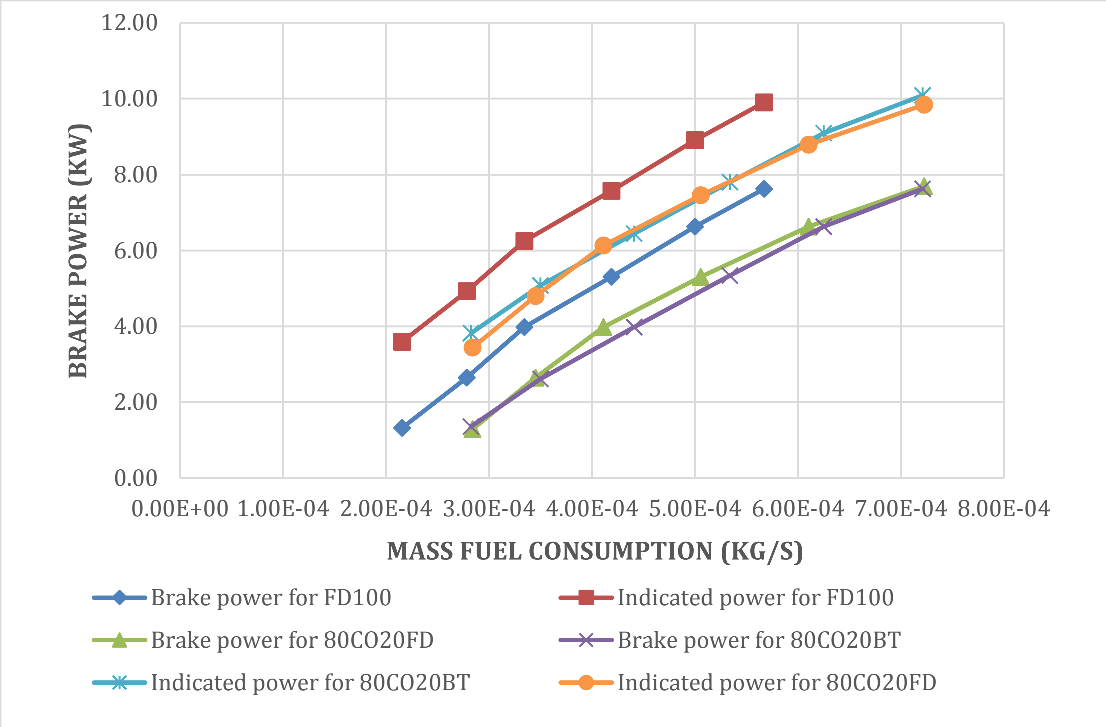


Figure 103: Brake and Indicated powers vs. Mass Fuel consumption of FD100 & CO100 and its blends.

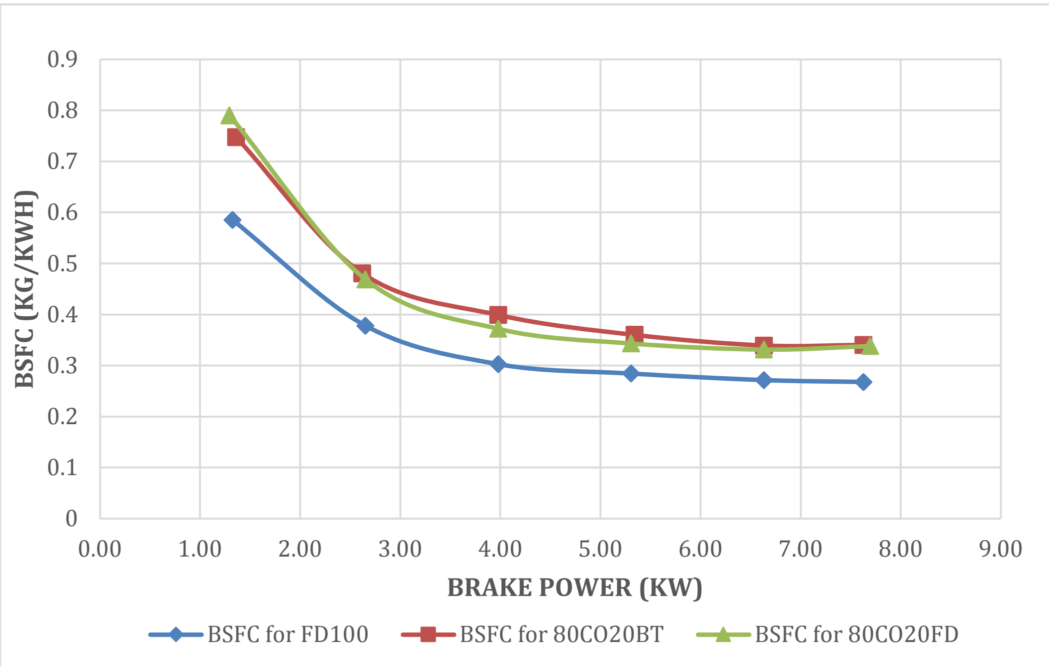


Figure 104: Brake Specific Fuel Consumption vs. load of FD100, CO100, and its blends.

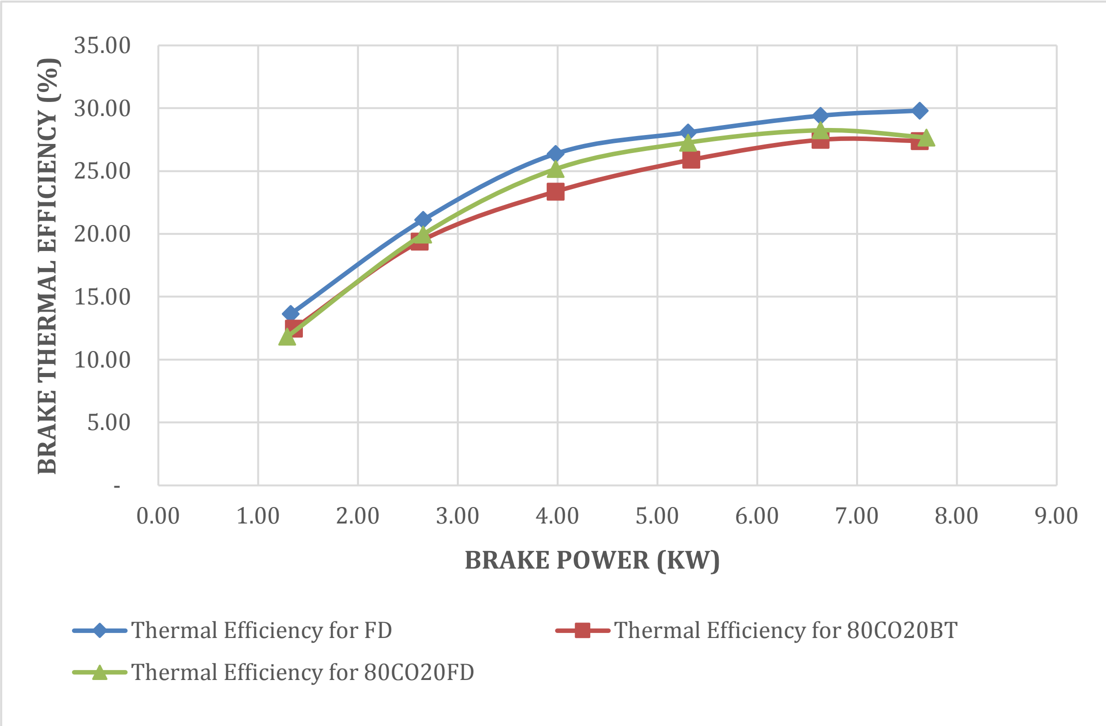


Figure 105: Brake Thermal Efficiency vs. load of CO100 and its blends.

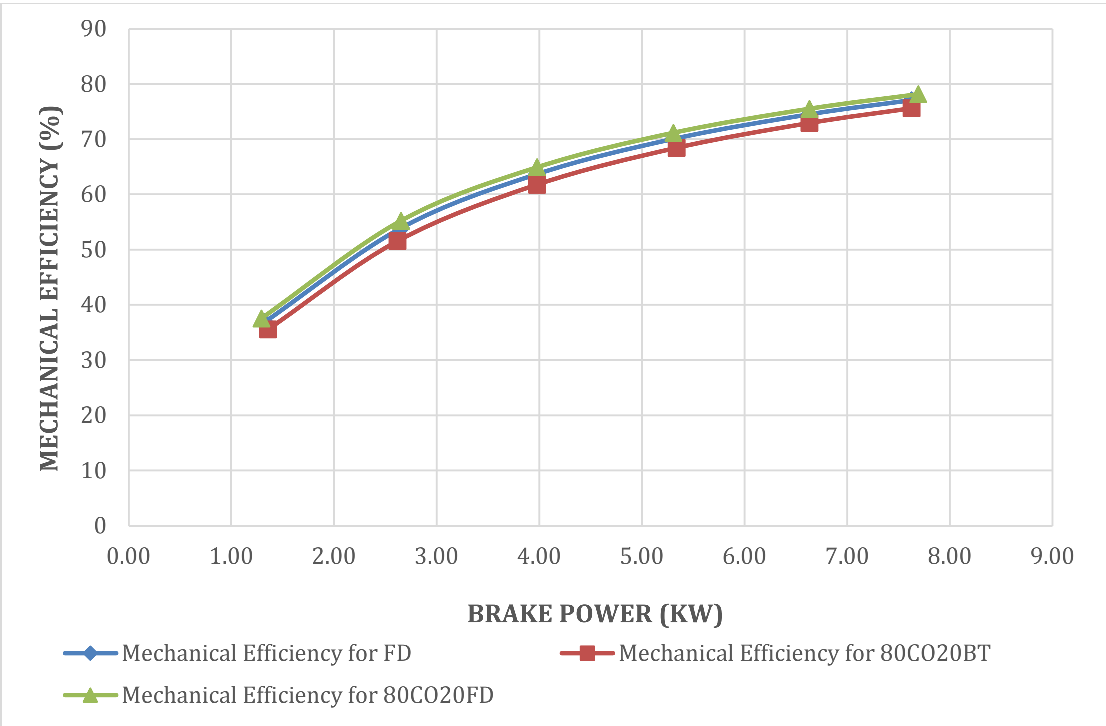


Figure 106: Mechanical Efficiency vs. load of FD100, CO100 and its blends.

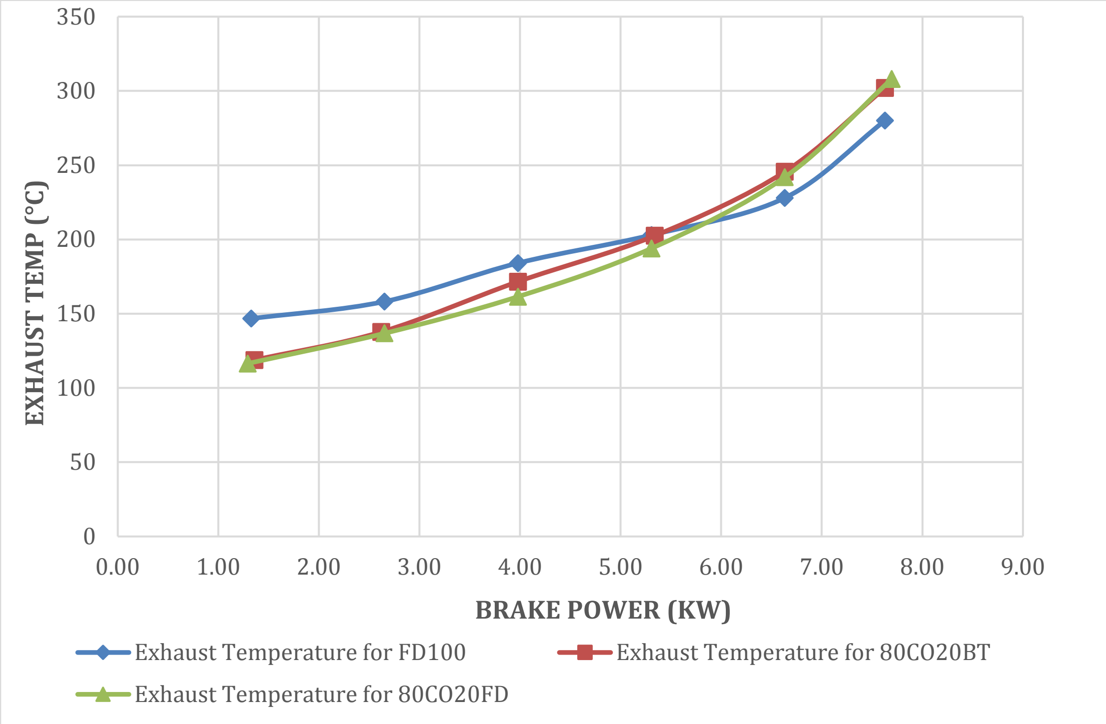


Figure 107: Exhaust temperature vs. load of FD100, CO100 and its blends.

6.4.2 Exhaust gas emissions

The Green House Gas (GHG) produced by 80CO20BT and 80CO20FD were measured and compared with FD100 emissions. As Figure 108 illustrates, Carbon Monoxide (CO) emissions of all sample were higher than that of FD100. At low load it were 92%, 56% upper than FD100 for 80CS20BT and 80CO20FD, respectively; while in high load, 80JA20BT and 80JA20FD showed increase in the range 15%- 37%, and 8%- 35%, respectively. High CO emissions of both samples attributed to the high oxygen content. Oxygen (O2) emissions show decreasing tendency with the increase of load (Figure 109) but no big difference from FD100; this attributed to the high compression ratio (high lambda) due to the amount of Oxygen in the fuels. Carbon Dioxide (CO2) of all samples inclusive FD100 were taken increasing tendency following the increase of load with exceptional in maximum load, the increase was higher, where 80CO20BT and 80JA20FD had shown 11% and 18% increase, respectively, on FD100. As it explained earlier, these fuels have higher consumption at maximum load which in return caused higher CO2 emissions.

From figure 111, shows that the hydrocarbon (HC) emissions of 80CO20FD developed in comparison with FD100 in all load; it fluctuates between 29% - 57%; this is due to the low combustion temperature of 80CO20FD in low load which was 26% lower than FD100. The low temperature could cause the air-fuel mixture not to combust as quick as the time of the power stroke permit. 80CO20BT has HC emissions which are 67% higher in low load while it fluctuates between 50% and 67% greater in medium and large loads; this could be attributed to the high temperature, relatively, comparing with 80CS20FD. During the other load, HC emission of all sample kept fluctuating but still higher that FD100 HC emissions; this is due to the variable operating conditions due to the high density and viscosity which could have caused untidy injection. As Figure 112 shows, Lambda of all sample showed consistency with a lambda of FD100. It was lower by 8% in all sample than FD100, except 80CO20FD which was around 4% higher than FD100 in low load; this could be due to the Oxygen content in the fuel which releases oxygen at the time of combustion; this oxygen rise lambda (the air-fuel ratio). In medium and higher load lambda for all sample was low. Low Lambda at these load is desirable since high lambda could cause knocking due to the high temperature of the mixture which causes high cylinder pressure.

Nitrogen Oxides (NO_X) as Figure 113 illustrates, reduced for all sample comparing with FD100. In low and medium loads NO_X reduction of 80CO20BT reached 84%, 57% respectively; while in high load reduction reached 24 %. 80CO20FD showed a low reduction of NO_X comparing to 80CO20BT; in low and medium loads showed 48%, 27% reduction respectively; while in high load it was 10% reduction; this attributed to the combustion temperatures. In low load the combustion temperatures were low (Figure 107) hence NO_X emission was low but when it raised up the NO_X emissions increased. Regarding smoke, 80CO20BT showed 20 - 72.73% higher smoke production than FD100, in low loads. In medium and large loads it reduced by 65.22% and 59.32%. 80CO20FD showed a reduction of 75% in low load, 66% in average load and 61.44% in high load. This low production level attributed to the high oxygen in all blend which helped proper combustion of all fuels.

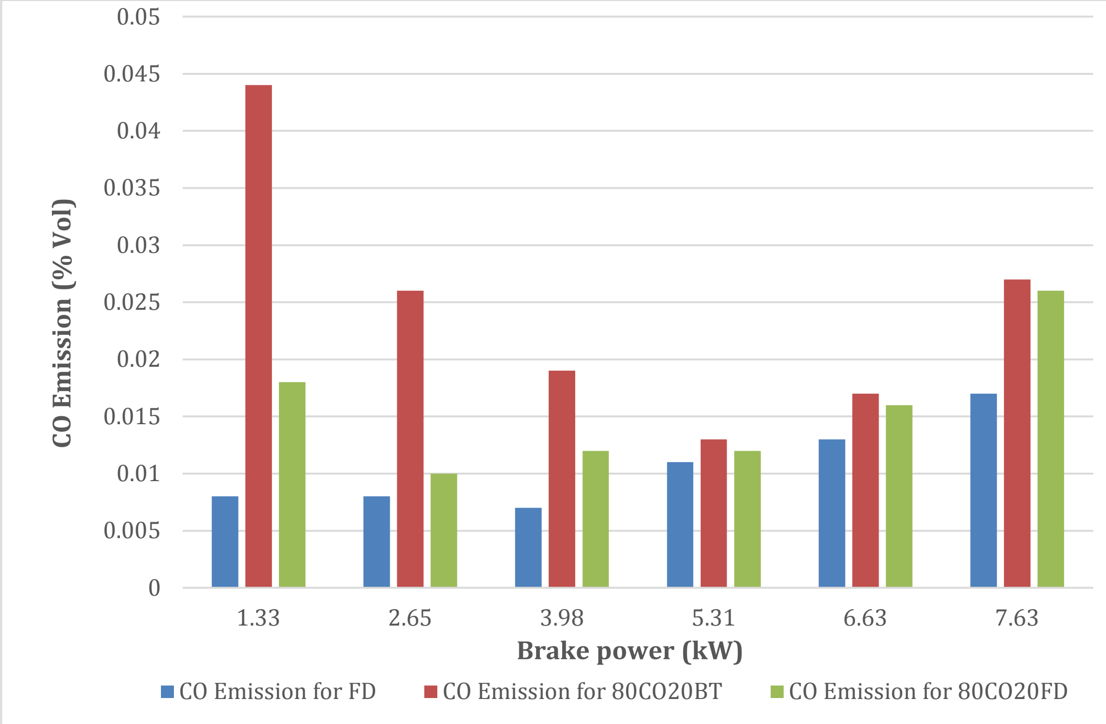


Figure 108: CO emission vs. load of FD100, CO100 and its blends.

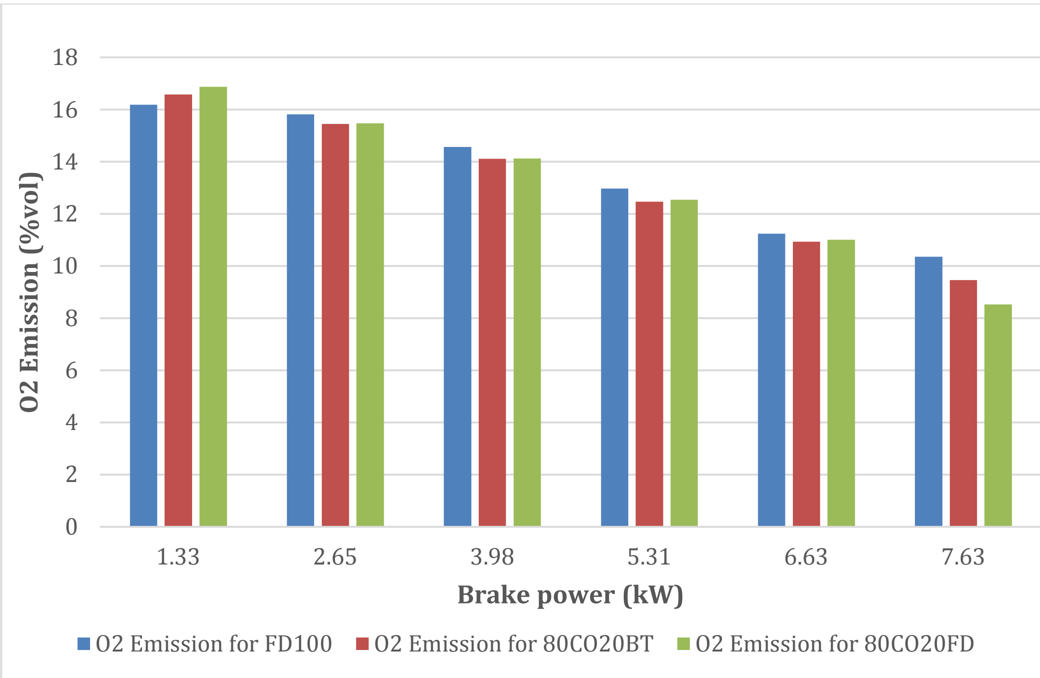


Figure 109: O2 emission vs. load of FD100, CO100 and its blends.

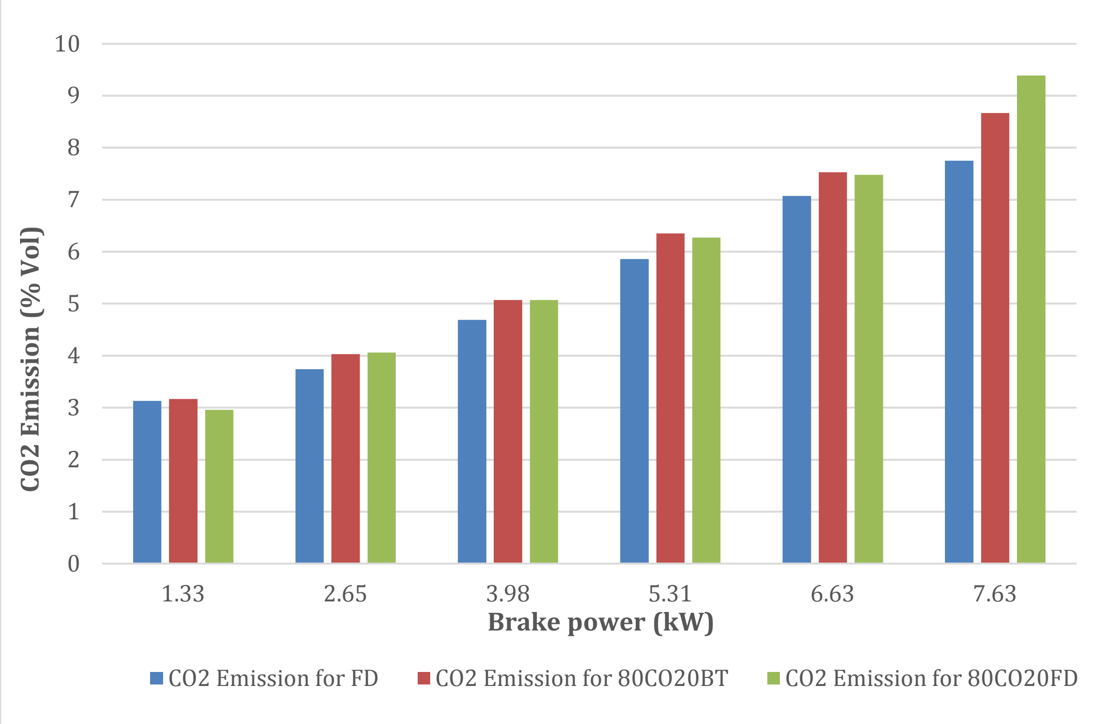


Figure 110: CO2 Emission vs. load of FD100, CO100 and its blends.

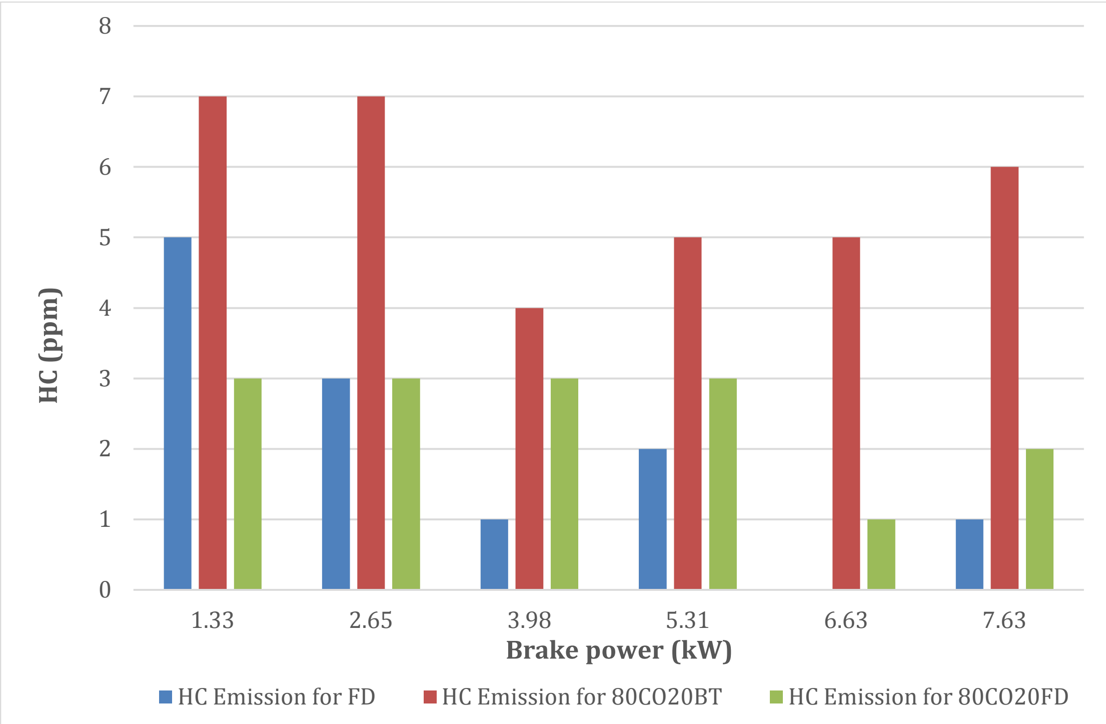


Figure 111: HC emission vs. load of FD100, CO100 and its blends.

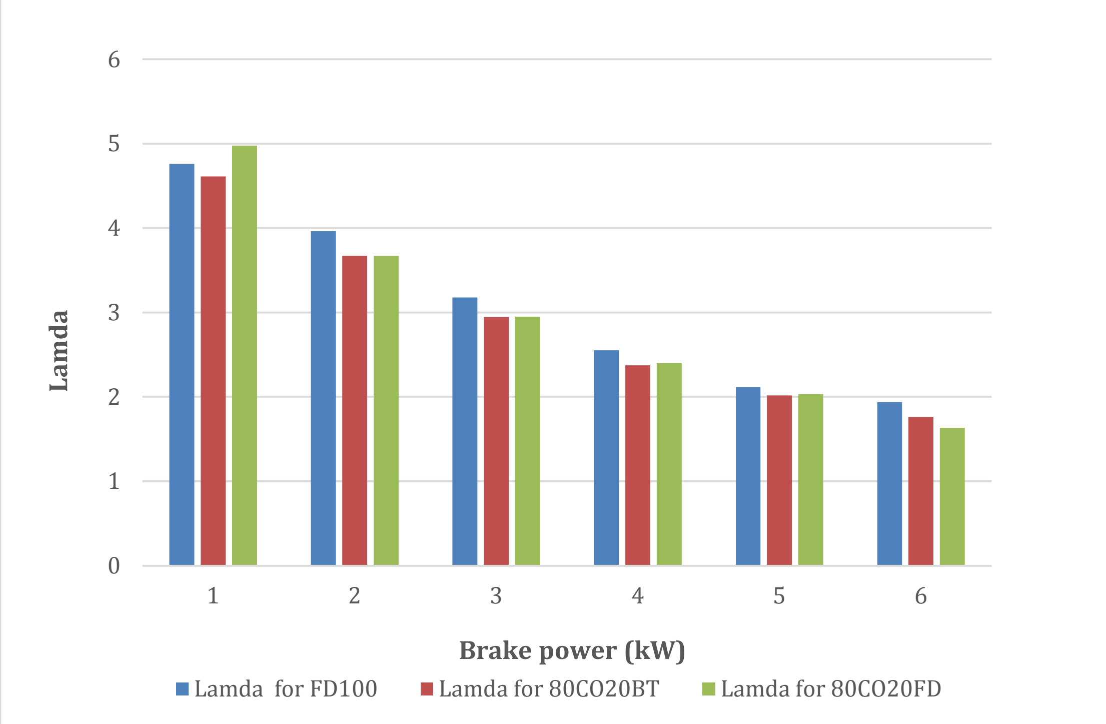


Figure 112: Lambda vs. load of FD100, CO100, and its blends.

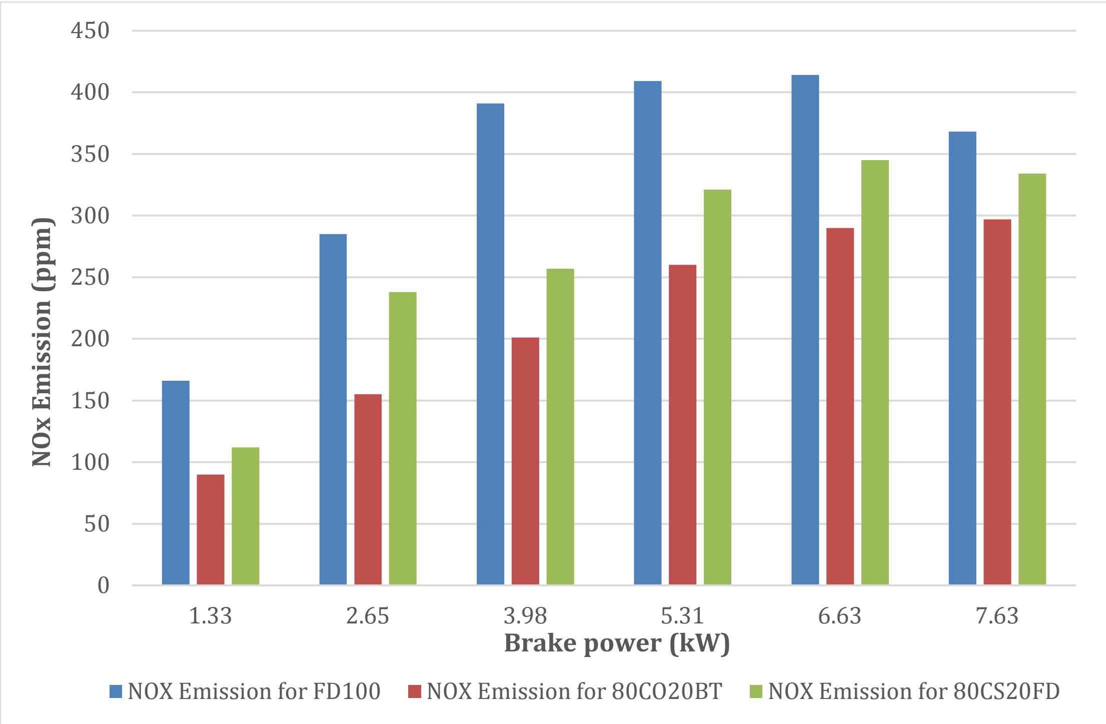


Figure 113: NO_X emission vs. load of FD100, CO100 and its blends.

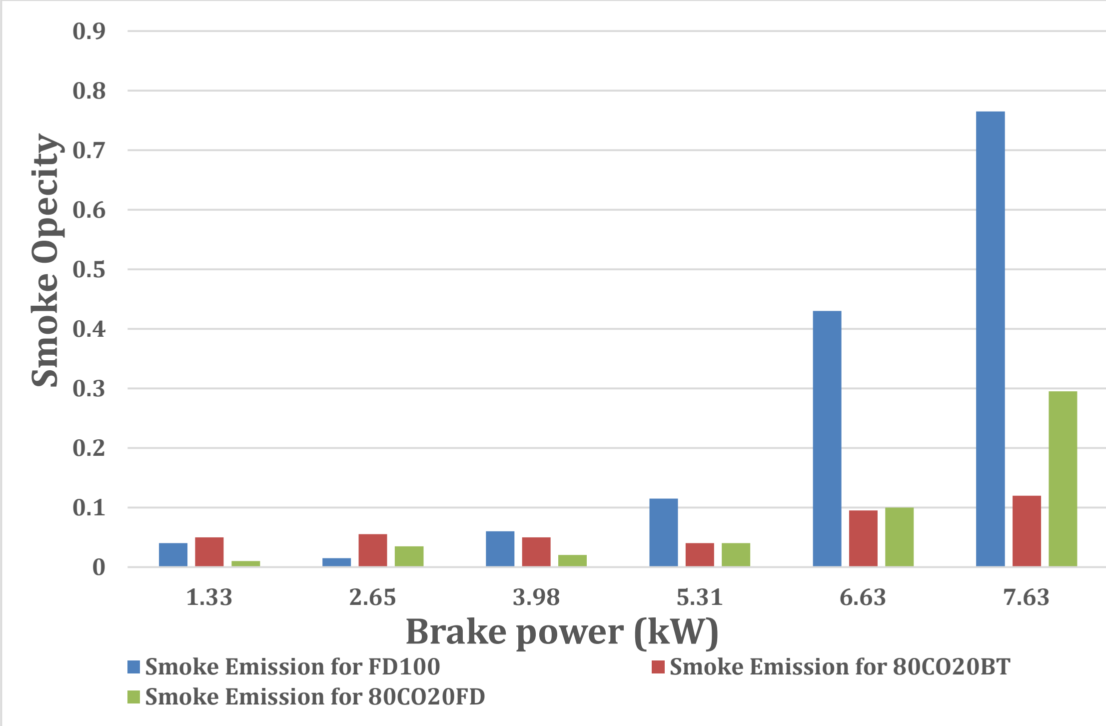


Figure 114: Smoke emission vs. load of FD100, CO100 and its blends.

6.5 Conclusions

All oils production which was testing in this study (CS100, JA100, CO100) whether as pure or in various blends with butanol or fossil diesel proved to be a suitable engine fuel in the scope of the test defined here. It shows promise as a potential biofuel source for small and community scale electricity generation in Sudan. To measure the effect of these biofuels in engine components and to analyze its durability, more extended engine testing required. Sudan is capable of increasing the production of these oil plants. Using these biofuels will help Sudan solve parts of its electricity generation problem as well as reducing GHG emissions.

Chapter 7: Conclusion and Recommendations

This study set out to objectively measure and assess implementation of various types of seed-based oils available in Sudan as sustainable biofuel to solve Sudan’s electricity generation deficit that occurred due to the loss of fossil fuel after secession in 2011.

The definite conclusions below will cover the key points from results and discussion of engine performance and exhaust emission using JA100, CS100 and CO100 and its blends as a fuel.

7.1 Conclusions

All indigestible oils production tested in this study (CS100, JA100, and CO100) whether as pure or in various blends with butanol or fossil diesel proved to be a suitable engine fuel in the scope of the test defined here. It shows promise as a potential biofuel source for small and community scale electricity generation in Sudan.

7.1.1 Detailed conclusions: Blending and characterisation

a) The blends were stable whether with ethanol, butanol or fossil diesel; except 80CS20ET which is not miscible.

b) The density of all biofuels were higher than FD100 by 8% - 13%. ; HHV values were lower by 14% - 23%. Kinematic viscosities (at 40°C) were 14% - 97% higher; while flashpoint were 44% -71% higher than FD100. Surface tension as literature shows was also high. It was 24.13 and 14.89 mN/m for both Cottonseed and Castor biofuels. No data found in the literature regarding Jatropha biofuel also biodiesel from Jatropha has 30.10 mN/m surface tension.

7.1.2 Detailed conclusions: Engine testing

a) JA100, 80JA20BT, 80JA20FD, CS100, 80CS20BT, 80CS20FD, 80CO20BT and 80CO20FD were tested successfully in a 7.4 kW indirect injection two-cylinder engine.

b) No combustion analysis is available in the used engine, but it predicted from other parameters.

c) In terms of BSFC, it were 18.4% higher than FD100 for JA100, 80JA20BT and 80JA20FD; for CS100, 80CS20BT and 80CS20FD it were 16% higher. 80CO20BT and 80CO20FD showed higher BSFC of 21% compared to FD100.

d) At maximum load, the brake thermal efficiency of JA100, 80JA20BT and 80JA20FD were 7% higher than FD100; while for CS100, 80CS20BT and 80CS20FD were 6.7% higher; it were 8% higher for both 80CO20BT and 80CO20FD.

e) Mechanical efficiency at maximum load for JA100, 80JA20BT,80JA20FD, CS100, 80CO20BT and 80CO20FD showed consistency with FD100; while for 80CS20BT and 80CS20FD it were higher by 9% and 15% respectively.

f) Regarding emissions, 80JA20BT showed 41%, 15.4%, 84%, higher CO, higher CO_2, and lower smoke productions respectively, compared to FD100 while 80JA20FD and JA100 showed 53%, 18%, 96% high CO, high CO_2 and low smoke productions, respectively. NOx emission for all JA100 and its blends have shown 5- 13% reduction.

g) 80CS20BT showed 35%, 15% increase of CO and CO_2 respectively; while CS100 and 80CS20FD showed 23% and 6% increase of CO, respectively; and 18% increase in CO_2. NOx and smoke production were reduced by 5-7 % and 62-91% respectively for all CS100 and its blends.

h) 80CO20BT and 80CO20FD showed 15-37%, 8 -35% increase of CO respectively; while for CO_2 increase it was 11% and 18% respectively. Both samples showed a reduction of NOx and smoke production in high load; for 80CO20BT and 80CO20FD were 24% and 10% respectively. Smoke production reduction showed 59.32- 65.22% for 80CO20BT and 61.44% for 80CO20FD.

The study concludes by this short-term engine testing that this CI engine type can be efficiently operated with 20% butanol blend of any of the three non-edible oils, Jatropha, Cottonseed and Castor oils, without any modification. Sudan has the potential of increasing the production of these three plant oils and butanol can be produced locally to minimise the cost of fossil diesel import. Although there is around 60 million litre of bioethanol production in Sudan in 2013, production of biobutanol will require a minor modification to the existing process. As the previous study showed[79] biobutanol has many advantages over bioethanol:

- It can be blend with higher ratio with diesel.
- Easy to transport in existing pipelines since the blend with bioethanol has high miscibility with water.
- Biobutanol has higher Low Heating Value (LHV) of 27.8 MJ/kg compared with 21.3 MJ/kg for bioethanol.
- Biobutanol has a high density and low vapour pressure which reflected on the low level of volatile organic compounds during handling.

The reduction of NO_X emission and smoke production could help Sudan reach its Green House Gas reduction target.

7.2 Recommendations

No doubt that the only option left for Sudan to solve its severe energy shortages is renewable energy; looking back to the enormous potential, the following can be recommended:

- Continue investment in hydropower, wind farm, and solar energies.
- Using the existing agricultural schemes as well as marginal lands to grow energy crops such as Jatropha, castor, cottonseed plants.
- Increase the research and investment in energy from industries waste and by-products; such as biofuels from sugar and oil industries.
- More extended engine testing for JA100, CS100, CO100 and its various blends to evaluate the effect on engines components and durability of biofuels.
- Using preheating of biofuels to solve viscosity problem by using stainless steel fuels pipes and heat exchangers to utilize the exhaust gas as a heating medium.
- Combine the use of non-edible seeds oil as biofuels with the utilization of the remaining cakes as feedstock for intermediate pyrolysis reactors; to maximize the efficient use of seeds and reduce the cost of obtaining biofuels.
- Using the biochar (by-product) of intermediate pyrolysis as fertilizer or soil enhancer to grow the new inedible plant for biofuels production.
- Investigate the utilization of the aqueous phase, which can be obtained during phase separation of the condensed liquid, in anaerobic digester plant.

References

[1] “Surah Ar-Rum [30:41] - Al-Qur’an al-Kareem - القرآن الكريم.” [Online]. Available: https://quran.com/30/41. [Accessed: 03-Mar-2017].

[2] infoplease, “Sudan,” 2014. [Online]. Available: http://www.infoplease.com/country/sudan.html?pageno=1. [Accessed: 13-Jul-2016].

[3] FAO, “AQUASTAT: Country Fact Sheet Sudan,” 2015.

[4] U. S. E. I. Administration, “Country Analysis Brief: Sudan and South Sudan.” 2014.

[5] BBC News, “Q&A: Sudan’s Darfur conflict,” 2010. [Online]. Available: http://news.bbc.co.uk/1/hi/world/africa/3496731.stm. [Accessed: 14-Jul-2016].

[6] A. Pedersen and M. Bazilian, “Considering the impact of oil politics on nation building in the Republic of South Sudan,” *Extr. Ind. Soc.*, vol. 1, no. 2, pp. 163–175, 2014.

[7] “SUDAN’S OIL PRODUCTION, REFINING CAPACITY CLIMB,” *OIL&GAS J.*, vol. 105, no. 20, 2007.

[8] IEA, “April: Biofuels can provide up to 27% of world transportation fuel by 2050, IEA report says - IEA ‘roadmap’ shows how biofuel production can be expanded in a sustainable way, and identifies needed technologies and policy actions,” 2011. [Online]. Available: https://www.iea.org/.

[9] IEA, “Renewable energy continuing to increase market share,” 2016. [Online]. Available: https://www.iea.org/newsroomandevents/news/2016/july/renewable-energy-continuing-to-increase-market-share.html. [Accessed: 28-Jul-2016].

[10] A. M. Omer, “Wind energy in Sudan,” *Renew. Energy*, vol. 19, no. 3, pp. 399–411, 2000.

[11] A. D. Mukasa, E. Mutambatsere, Y. Arvanitis, and T. Triki, "Wind energy in sub-Saharan Africa: Financial and political causes for the sector's under-development," *Energy Res. Soc. Sci.*, vol. 5, pp. 90–104, 2015.

[12] A. M. Omer, "Sudan energy background; An overview," *Renew. Energy*, vol. 14, no. 1–4, pp. 467–472, 1998.

[13] A. M. Omer, "On the wind energy resources of Sudan," *Renew. Sustain. Energy Rev.*, vol. 12, no. 8, pp. 2117–2139, 2008.

[14] A. M. Omer, "Wind energy in Sudan: Water pumping in rural areas," *Refocus*, vol. 2, no. 8, pp. 34–37, 2001.

[15] J. T. Robert Gasch, Ed., "Wind Power Plants," *Fundamentals, Design, Construction and Operation*. Springer Science & Business Media, Germany, p. 535, 2012.

[16] "Phys.org - solar energy." [Online]. Available: https://phys.org/tags/solar energy/. [Accessed: 03-Mar-2017].

[17] J. a. Duffie, W. a. Beckman, and W. M. Worek, *Solar Engineering of Thermal Processes, 4nd ed.*, vol. 116. 2003.

[18] G. R. Timilsina, L. Kurdgelashvili, and P. A. Narbel, "Solar energy: Markets, economics and policies," *Renew. Sustain. Energy Rev.*, vol. 16, no. 1, pp. 449–465, Jan. 2012.

[19] H. Ruihui, "Classified Book and the Forming of China Culture and Literature Stereotypes," vol. 3, no. 2, pp. 143–153, 2016.

[20] R. Perez and M. Perez, "A Fundamental Look At Supply Side Energy Reserves For The Planet," *Int. energy Agency SHC Program. Sol. Updat.*, pp. 4–6, 2015.

[21] V. V. Tyagi, N. A. A. Rahim, N. A. Rahim, and J. A. /L. Selvaraj, "Progress in solar PV technology: Research and achievement," *Renew. Sustain. Energy Rev.*, vol. 20, pp. 443–461, Apr. 2013.

[22] V. Devabhaktuni, M. Alam, S. Shekara Sreenadh Reddy Depuru, R. C. Green, D. Nims, and C. Near, "Solar energy: Trends and enabling technologies,"

Renew. Sustain. Energy Rev., vol. 19, pp. 555–564, Mar. 2013.

[23] A. M. Omer, "Compilation and evaluation of solar and wind energy resources in Sudan," *Renew. Energy*, vol. 12, no. 1, pp. 39–69, 1997.

[24] S. S. Ali, "Solar desalination in Sudan," *Desalination*, vol. 93, no. 1–3, pp. 581–585, 1993.

[25] U.S. Energy Information Administration (eia), "U.S. Energy Information Administration (eia)," 2016. [Online]. Available: http://www.eia.gov/energyexplained/index.cfm?page=solar_where. [Accessed: 20-May-2016].

[26] T. M. Razykov, C. S. Ferekides, D. Morel, E. Stefanakos, H. S. Ullal, and H. M. Upadhyaya, "Solar photovoltaic electricity: Current status and future prospects," *Sol. Energy*, vol. 85, pp. 1580–1608, 2011.

[27] M. M. Hoogwijk, "ON THE GLOBAL AND REGIONAL POTENTIAL OF RENEWABLE ENERGY SOURCES," 2004.

[28] T. Bradford, *Solar revolution : the economic transformation of the global energy industry*. MIT Press, 2006.

[29] REN21, *Global Status Rport*. 2014.

[30] M. Moner-Girona, R. Ghanadan, A. Jacobson, and D. M. Kammen, "Decreasing PV costs in Africa," *Refocus*, vol. 7, no. 1, pp. 40–45, Jan. 2006.

[31] A. M. Omer, "Solar water pumping clean water for Sudan rural areas," *Renew. Energy*, vol. 24, no. 2, pp. 245–258, 2001.

[32] N. A. Elagib and M. G. Mansell, "New approaches for estimating global solar radiation across Sudan," *Energy Convers. Manag.*, vol. 41, no. 5, pp. 419–434, 2000.

[33] A. M. Omer, "Renewable energy resources for electricity generation in Sudan," *Renew. Sustain. Energy Rev.*, vol. 11, no. 7, pp. 1481–1497, 2007.

[34] UNDP, "Onto the Future: Solar Energy in Sudan:Serving the Environment, Development and Agricultural Sectors," 2014. [Online]. Available:

http://www.sd.undp.org/content/sudan/en/home/ourwork/environmentandenergy/successstories/Solar_Energy_in_Sudan.html#. [Accessed: 24-May-2016].

[35] Soteris Kalogirou, *Solar energy engineering : processes and systems*, 1st ed. California: Elsevier Inc., 2009.

[36] ATKINSON RENEWABLE ENERGY, "Solar thermal (heat)," 2016. [Online]. Available: http://www.atkinson-builders.co.uk/atkinson-renewables/products-services/solar-thermal-heat/. [Accessed: 29-May-2016].

[37] FAO, "FAOSTAT, Sudan," 2016. [Online]. Available: http://faostat3.fao.org/browse/area/276/E. [Accessed: 21-Jul-2016].

[38] M. Hassan, "Modelling and simulation of biomass gasification in a circulating fluidized bed reactor Modelling and simulation of biomass gasification in a circulating fluidized bed reactor," Aston University,Birmingham, 2013.

[39] K. Kaygusuz and M. F. Türker, "Biomass energy potential in Turkey," *Renew. Energy*, vol. 26, no. 4, pp. 661–678, 2002.

[40] A. M. Omer and Y. Fadalla, "Biogas energy technology in Sudan," *Renew. Energy*, vol. 28, no. 3, pp. 499–507, Mar. 2003.

[41] "05/00749 Biomass energy potential and future prospect in Sudan," *Fuel Energy Abstr.*, vol. 46, no. 2, pp. 110–111, 2005.

[42] WBA, "GLOBAL BIOMASS POTENTIAL TOWARDS 2035," no. March, p. 6, 2016.

[43] R. Hassan, G. Hertzler, and J. K. A. A. Benhin, "Depletion of forest resources in Sudan: Intervention options for optimal control," *Energy Policy*, vol. 37, no. 4, pp. 1195–1203, 2009.

[44] S. El Tayeb Muneer and E. W. Mukhtar Mohamed, "Adoption of biomass improved cookstoves in a patriarchal society: an example from Sudan," *Sci. Total Environ.*, vol. 307, no. 1–3, pp. 259–266, 2003.

[45] R. M. Hassan and G. Hertzler, "Deforestation from the overexploitation of

wood resources as a cooking fuel: A dynamic approach to pricing energy resources in Sudan," *Energy Econ.*, vol. 10, no. 2, pp. 163–168, 1988.

[46] A. Omer, "Review Article Energy , Environment , and Sustainable Development in Sudan," vol. 2, no. 1, pp. 31–44, 2011.

[47] B. C. Arimah and O. J. Ebohon, "Energy transition and its implications for environmentally sustainable development in Africa," *Int. J. Sustain. Dev. World Ecol.*, vol. 7, no. 3, pp. 201–216, 2000.

[48] H. F. Abdelraheem, A. Lang, and M. E. A. Elsayed, "Jatropha curcas: A viable alternative source of clean energy to meet Sudan's growing energy demand," in *Proceedings - 2013 International Conference on Computer, Electrical and Electronics Engineering: "Research Makes a Difference", ICCEEE 2013*, 2013, pp. 287–293.

[49] THE WORLD BANK, "Sudan Overiew," 2016. [Online]. Available: http://www.worldbank.org/en/country/sudan/overview. [Accessed: 17-Jun-2016].

[50] F. Mahgoub, "Current Status of Agriculture and Future Challenges in Sudan."

[51] The World Bank, "THE WORLD BANK Poverty Reduction and Economic Management Unit | Africa Region Sudan The Road Toward Sustainable and Broad-Based Growth," 2009.

[52] United States. Department of State. Bureau of Public Affairs, "Sudan.," *Backgr. Notes Ser.*, pp. 1–8, Aug. 1985.

[53] A.-J. S. C. Channel, "(76) إنتاج الوقود الحيوي من نبتة الجاتروفا في السودان - YouTube," 2012. [Online]. Available: https://www.youtube.com/watch?v=js01W_WOzbg. [Accessed: 13-Jun-2017].

[54] Our Africa, "Climate & Agriculture," 2016. [Online]. Available: http://www.our-africa.org/sudan/climate-agriculture. [Accessed: 15-Jun-2016].

[55] P. Availabilithy and M. Ramaswami, "Scientific Processing of Cottonseed:

Need of The Hour," Mumbai, 2011.

[56] P. McKendry, "Energy production from biomass (part 1): Overview of biomass," *Bioresour. Technol.*, vol. 83, no. 1, pp. 37–46, 2002.

[57] P. Helena and B. Sanchez, "NICKEL BASED CATALYSTS FOR HYDROGEN PRODUCTION FROM THE PYROLYSIS / GASIFICATION OF REFUSE DERIVED FUEL (RDF) By," no. June, 2014.

[58] A. M. Omer, "Biomass energy potential and future prospect in Sudan," *Renew. Sustain. Energy Rev.*, vol. 9, no. 1, pp. 1–27, 2005.

[59] M. Alhadi, A. Magzoub, A. Mohmmed, G. Hussein, M. Nabil, B. H. Osman, and M. Adam, "Investigating the Solid Waste Management Problems in Urban Area, Sudan," vol. 3, no. 6, pp. 947–953, 2014.

[60] FAO, "Food Loss and Food Waste." [Online]. Available: http://www.fao.org/food-loss-and-food-waste/en/. [Accessed: 22-Jun-2016].

[61] A. M. Omer, "Sustainable Green Energies Development and Promoting New Technologies," *Glob. J. Sci. Front. Res.*, vol. 12, no. 3 Version 1.0, 2012.

[62] Y. Yang, J. G. Brammer, J. Samanya, A. K. Hossain, and A. Hornung, "Investigation into the performance and emissions of a stationary diesel engine fuelled by sewage sludge intermediate pyrolysis oil and biodiesel blends," *Energy*, vol. 62, pp. 269–276, 2013.

[63] J. Ben-Iwo, V. Manovic, and P. Longhurst, "Biomass resources and biofuels potential for the production of transportation fuels in Nigeria," *Renew. Sustain. Energy Rev.*, vol. 63, pp. 172–192, 2016.

[64] A. M. Omer, "Overview of renewable energy sources in the Republic of the Sudan," *Energy*, vol. 27, no. 6, pp. 523–547, 2002.

[65] A. K. Hossain, C. Serrano, J. B. Brammer, A. Omran, F. Ahmed, D. I. Smith, and P. A. Davies, "Combustion of fuel blends containing digestate pyrolysis oil in a multi-cylinder compression ignition engine," *Fuel*, vol. 171, pp. 18–28, May 2016.

[66] P. McKendry, "Energy production from biomass (part 3): gasification technologies," *Bioresour. Technol.*, vol. 83, no. 1, pp. 55–63, 2002.

[67] R. Sims and M. Taylor, "An overview of current industry and RD&D activities INTERNATIONAL ENERGY AGENCY ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT," 2008.

[68] V. Thomas and A. Kwong, "Ethanol as a lead replacement: phasing out leaded gasoline in Africa," *Energy Policy*, vol. 29, no. 13, pp. 1133–1143, 2001.

[69] "Kenana Sugar Company - Products and Services - Ethanol," 2016. [Online]. Available: http://www.kenana.com/pagecontents.aspx?pageid=24. [Accessed: 31-Aug-2016].

[70] ARISE NEWS, "Sudan banking on biofuels - YouTube," 2013. [Online]. Available: https://www.youtube.com/watch?v=UryuDCn2rtY. [Accessed: 01-Sep-2016].

[71] A. Nalgundwar, B. Paul, and S. K. Sharma, "Comparison of performance and emissions characteristics of DI CI engine fueled with dual biodiesel blends of palm and jatropha," *Fuel*, vol. 173, pp. 172–179, 2016.

[72] S. M. Gmü Nder, R. Zah, S. Bhatacharjee, M. Classen, P. Mukherjee, and R. Widmer, "Life cycle assessment of village electrification based on straight jatropha oil in Chhattisgarh, India," *Biomass and Bioenergy*, vol. 34, pp. 347–355, 2009.

[73] P. Pati, "SUSTAINABILITY OF JATROPHA CULTIVATION FOR BIODIESEL FUELS," Michigan State University, 2015.

[74] B. N. Divakara, H. D. Upadhyaya, S. P. Wani, and C. L. L. Gowda, "Biology and genetic improvement of Jatropha curcas L.: A review," *Appl. Energy*, vol. 87, no. 3, pp. 732–742, 2010.

[75] F. on H. and the E. GreenFacts, "Liquid Biofuels for Transport Prospects, risks and opportunities," 2016. [Online]. Available: http://www.greenfacts.org/en/biofuels/l-3/3-markets-production-

evolution.htm#0p0. [Accessed: 27-Jul-2016].

[76] K. Senelwa, L. Etiégni, O. Osano, K. Balozi, and M. Imo, "Environmental impacts of biofuel production in Africa," in *Bioenergy for sustainable development in Africa*, 2014, pp. 237–245.

[77] Questacon - The National Science and Technology Centre, "Oil and Water." [Online]. Available: https://www.questacon.edu.au/outreach/programs/science-circus/videos/oil-and-water. [Accessed: 08-Mar-2017].

[78] The HUMAN TOUCH of Chemistry, "Everyday Chemistry - Why Oil and Water do not mix?" [Online]. Available: http://humantouchofchemistry.com/why-oil-and-water-do-not-mix.htm. [Accessed: 08-Mar-2017].

[79] J. Swana, Y. Yang, M. Behnam, and R. Thompson, "An analysis of net energy production and feedstock availability for biobutanol and bioethanol," *Bioresour. Technol.*, vol. 102, no. 2, pp. 2112–2117, Jan. 2011.

[80] M. . Cengel, Y.A and Boles, *Thermodynamics An Engineering Approach*, 7th ed. New York: McGraw-Hill, 2011.

[81] R. S. Jessup, "Precise Measurement of Heat of Combustion With a Bomb Calorimeter," 1960.

[82] A. Martyr and M. A. (Michael A. Plint, *Engine testing : theory and practice*. Butterworth-Heinemann, 2007.

[83] L. L. PETTER, "LPW, LPWS & Turbo engines WORKSHOP MANUAL," Dursley.

[84] K. Pramanik, "Properties and use of Jatropha curcas oil and diesel fuel blends in compression ignition engine," *Renew. Energy*, vol. 28, no. 2, pp. 239–248, 2003.

[85] R. D. Misra and M. S. Murthy, "Straight vegetable oils usage in a compression ignition engine—A review," *Renew. Sustain. Energy Rev.*, vol. 14, no. 9, pp. 3005–3013, 2010.

[86] A. K. Hossain and P. A. Davies, "Plant oils as fuels for compression ignition

engines: A technical review and life-cycle analysis," *Renew. Energy*, vol. 35, no. 1, pp. 1–13, 2010.

[87] A. E. Atabani, A. S. Silitonga, I. A. Badruddin, T. M. I. Mahlia, H. H. Masjuki, and S. Mekhilef, "A comprehensive review on biodiesel as an alternative energy resource and its characteristics," *Renew. Sustain. Energy Rev.*, vol. 16, no. 4, pp. 2070–2093, 2012.

[88] J. Thangaraja, K. Anand, and P. S. Mehta, "Biodiesel NOx penalty and control measures - a review," *Renew. Sustain. Energy Rev.*, vol. 61, pp. 1–24, 2016.

[89] A. . Ramadhas, S. Jayaraj, and C. Muraleedharan, "Use of vegetable oils as I.C. engine fuels—A review," 2004.

[90] M. Canakci and H. Sanli, "Biodiesel production from various feedstocks and their effects on the fuel properties," *J. Ind. Microbiol. {&} Biotechnol.*, vol. 35, no. 5, pp. 431–441, 2008.

[91] S. A. Basha, K. R. Gopal, and S. Jebaraj, "A review on biodiesel production, combustion, emissions and performance," *Renew. Sustain. Energy Rev.*, vol. 13, no. 6, pp. 1628–1634, 2009.

[92] M. N. Nabi, M. M. Rahman, and M. S. Akhter, "Biodiesel from cotton seed oil and its effect on engine performance and exhaust emissions," *Appl. Therm. Eng.*, vol. 29, no. 11–12, pp. 2265–2270, 2009.

[93] S.-Y. Y. No, "Inedible vegetable oils and their derivatives for alternative diesel fuels in CI engines: A review," *Renew. Sustain. Energy Rev.*, vol. 15, no. 1, pp. 131–149, 2011.

[94] N. Siddiqui and A. Ahmad, "a Study on Viscosity , Surface Tension and Volume," vol. 2, no. 6, pp. 1318–1326, 2013.

[95] B. Esteban, J.-R. Riba, G. Baquero, R. Puig, and A. Rius, "Characterization of the surface tension of vegetable oils to be used as fuel in diesel engines," *Fuel*, vol. 102, pp. 231–238, Dec. 2012.

[96] V. Scholz and J. N. da Silva, "Prospects and risks of the use of castor oil as a

fuel," *Biomass and Bioenergy*, vol. 32, no. 2, pp. 95–100, 2008.

[97] L. Canoira, J. García Galeán, R. Alcántara, M. Lapuerta, and R. García-Contreras, "Fatty acid methyl esters (FAMEs) from castor oil: Production process assessment and synergistic effects in its properties," *Renew. Energy*, vol. 35, no. 1, pp. 208–217, 2010.

[98] N. L. L. Panwar, H. Y. Shrirame, N. S. S. Rathore, S. Jindal, and A. K. K. Kurchania, "Performance evaluation of a diesel engine fueled with methyl ester of castor seed oil," 2010.

[99] G. Hincapié, F. Mondragón, and D. López, "Conventional and in situ transesterification of castor seed oil for biodiesel production," *Fuel*, vol. 90, no. 4, pp. 1618–1623, 2011.

[100] V. SathyaSelvabala, T. K. Varathachary, D. K. Selvaraj, V. Ponnusamy, and S. Subramanian, "Removal of free fatty acid in Azadirachta indica (Neem) seed oil using phosphoric acid modified mordenite for biodiesel production," *Bioresour. Technol.*, vol. 101, no. 15, pp. 5897–5902, 2010.

[101] M. N. Nabi, M. S. Akhter, and M. M. Z. Shahadat, "Improvement of engine emissions with conventional diesel fuel and diesel-biodiesel blends," *Bioresour. Technol.*, vol. 97, no. 3, pp. 372–378, 2006.

[102] N. R. Banapurmath, P. G. Tewari, V. S. Yaliwal, S. Kambalimath, and Y. H. Basavarajappa, "Combustion characteristics of a 4-stroke CI engine operated on Honge oil, Neem and Rice Bran oils when directly injected and dual fuelled with producer gas induction," *Renew. Energy*, vol. 34, no. 7, pp. 1877–1884, Jul. 2009.

[103] M. Mohibbe Azam, A. Waris, and N. M. Nahar, "Prospects and potential of fatty acid methyl esters of some non-traditional seed oils for use as biodiesel in India," *Biomass and Bioenergy*, vol. 29, no. 4, pp. 293–302, 2005.

[104] A. Karmakar, S. Karmakar, and S. Mukherjee, "Biodiesel production from neem towards feedstock diversification: Indian perspective," *Renew. Sustain. Energy Rev.*, vol. 16, no. 1, pp. 1050–1060, 2012.

[105] A. Dhar, R. Kevin, and A. K. Agarwal, "Production of biodiesel from high-FFA neem oil and its performance, emission and combustion characterization in a single cylinder DICI engine," *Fuel Process. Technol.*, vol. 97, pp. 118–129, 2012.

[106] M. Y. Liauw, F. A. Natan, P. Widiyanti, D. Ikasari, N. Indraswati, and F. E. Soetaredjo, "EXTRACTION OF NEEM OIL (Azadirachta indica A. Juss) USING N-HEXANE AND ETHANOL: STUDIES OF OIL QUALITY, KINETIC AND THERMODYNAMIC," vol. 3, no. 3, 2008.

[107] S. S. Ragit, S. K. Mohapatra, K. Kundu, and & K. Kundu, "Comparative study of engine performance and exhaust emission characteristics of a single cylinder 4-stroke CI engine operated on the esters of hemp oil and neem oil," *Indian J. Eng. Mater. Sci.*, vol. 18, no. 3, pp. 204–210, 2011.

[108] M. J. Jacobus, S. M. Geyer, S. S. Lesfz, W. D. Taylor, and T. H. Risby, "Single-Cylinder Diesel Engine Study of Four Vegetable Oils," 1983.

[109] B. Samaga, "Vegetable oil as alternative fuels for C.I. engines," in *8th National Conference on I. C. Engines*, 1983.

[110] N. J. Barsic and A. L. Humke, "Performance and Emissions Characteristics of a Naturally Aspirated Diesel Engine with vegetable Oil Fuels," 1981.

[111] A. Saydut, M. Z. Duz, C. Kaya, A. B. Kafadar, and C. Hamamci, "Transesterified sesame (Sesamum indicum L.) seed oil as a biodiesel fuel," 2008.

[112] A. El Gasim, A. Yagoub, M. Khalid, S. El Khier, K. Elnur, A. Ishag, and A. Elgasim, "Chemical Composition and Oil Characteristics of Sesame Seed Cultivars Grown in Sudan," *Res. J. Agric. Biol. Sci.*, vol. 4, no. 6, pp. 761–766, 2008.

[113] N. R. Banapurmath, P. G. Tewari, and R. S. Hosmath, "Performance and emission characteristics of a DI compression ignition engine operated on Honge, Jatropha and sesame oil methyl esters," *Renew. Energy*, vol. 33, no. 9, pp. 1982–1988, 2008.

[114] Ş. Altun, H. Bulut, and C. Öner, "The comparison of engine performance and

exhaust emission characteristics of sesame oil-diesel fuel mixture with diesel fuel in a direct injection diesel engine," *Renew. Energy*, vol. 33, no. 8, pp. 1791–1795, 2008.

[115] A. M. Omer, A.M. Omer ∗, and A. M. Omer, "Overview of renewable energy sources in the Republic of the Sudan," *Energy*, vol. 27, no. 6, pp. 523–547, 2000.

[116] "A P R I L 2 0 1 7," 2017. [Online]. Available: http://www.virginiadot.org/business/const/calendar-apr.asp. [Accessed: 03-Mar-2017].

Appendices

Appendix A

Fuels characterisation procedures

High Heating Value testing procedure

The apparatus used to measure high heating value (HHV) is Parr 6100 Calorimeter and Accessories (ASTM D420-90) as Figure 40 illustrates. The measurement accuracies are ±0.1%.

Before test of samples commences the machine should be standardized. This standardization will be done using a sample with known higher heat value (HHV). The benzoic acid used due to its ability to burn completely in oxygen. The standardization achieved in the same way, but the HHV is known, and the energy equivalent (EE) calculated as follow:

EE (Cal/°C) = (weight of benzoic acid x HHV)/ (temperature rise).

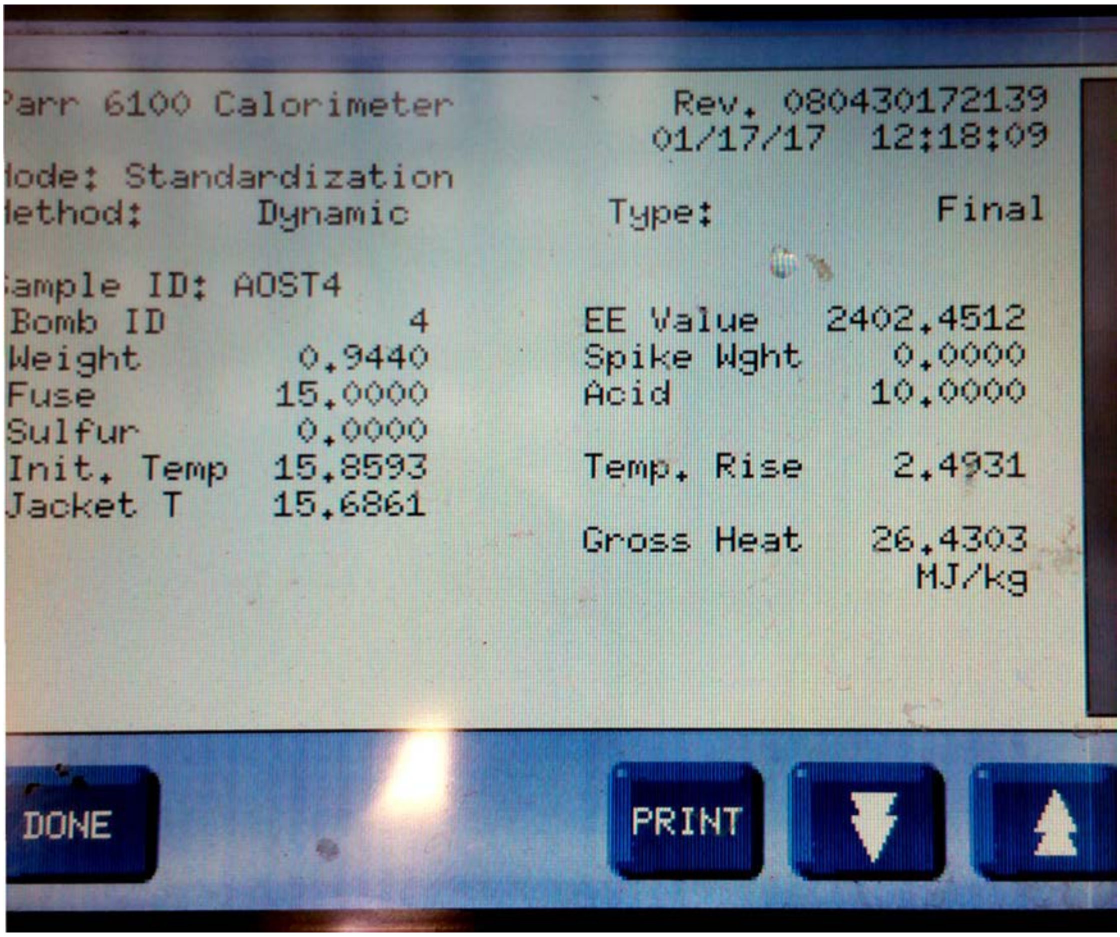


Figure 1: Standardization of Parr 6100 Calorimeter.

Before the measurement of all sample, Calorimeter standardized as figure 1 shows. To reach EE value of around 2400 and gross heat of around 26.4 four-runs was done.

EE defined as the amount of energy required to raise the temperature of the machine by one degree[116]. The standardization and sample test following the same procedure. The only difference is that during check the mode should be determination:

- The sample measured by precision balance using the crucible as a container.
- The sample placed on the holder of the electrode loop then connected with the fuse wire. It was done carefully that the wire does not touch the sample or the crucible.
- The Bomb head was put back on the bomb, and the screw cap turned until it was completely locked.
- Gas release valve was turned to close.
- The bomb put near the calorimeter, and the gas wire should be connected, the gas cylinder should be open. When the signal heard, the wire has to be disconnected.
- The calorimeter was left for 20 minutes to stabilize.
- O2 fill on the touch screen pressed.
- In the case of calibration, the screen shows standardization and an in the case of regular test, determination.
- The bucket should was filled with 2000g of distilled water.
- The bucket put in the bucket jacket.
- The bomb was held with a handle and placed in the bucket.
- The handle was disconnected carefully by removing any water.
- The two bananas wire connected to the bomb.
- Calorimeter cover closed, and start bottom pressed.
- By following the instruction on screen, the sample and bomb IDs and the sample weight entered.
- It had taken around 20 minutes before it gave a result of the screen or an error in case of misfire.
- By pressing Done Button the value of EE saved in the event of standardization or all the result on the occasion of sample test.
- The calorimeter opened, and the bananas wire was disconnected, and the bomb was taken out.
- The bucket was taken out.

The bomb was depressurized by turning the gas release valve to open.

The screw cap opened.

The bomb and crucible washed with water, and it is ready for next run.

Viscosity testing procedure

- The viscometer cleaned with acetone; one of its advantages, it dries quickly.
- The viscometer was inverted, and the broader tube immersed in FD sample.
- Suction applied to the smaller tube, and FD sucked until it passes point one.
- The viscometer turned into normal position.
- Tube N wiped with a clean tissue.
- The temperature set to 40 °C on the thermostat after the water bath filled with water.
- When the temperature of the water bath reached 40 °C, the viscometer inserted into the water bath by using the Adjustable Holder.
- Viscometer needed around 10 minutes to come to the bath temperature.
- Suction was applied to the smaller tube to draw FD to above point one.
- FD was allowed to flow down freely.
- The time it took to pass between point one, and two was recorded (Figure *41*).
- The last three steps were repeated twice to eliminate any human error.
- The time recorded was multiplied by Viscometer constant (0.5492) to calculate the kinematic viscosity in cSt (mm2/s).

- All the steps repeated in the same way for the other samples.

Density testing procedure

A hydrometer used to measure density, :(room temperature was 16 - 25°C)

- The fuel sample poured in a tubular cylinder (Figure *42*).
- The room temperature was measured.
- The hydrometer lowered into the cylinder.
- After the letting the hydrometer to settle, density read of the Hydrometer.
- The reading is the alignment of the hydrometer with the top of the fuel sample.

Flashpoint testing procedure

The flash points were measured using, SETA Flashpoint tester ASTM D3278 which is compact benchtop/portable instruments (Figure 43). This tester is not complicated to use. It can finish the test in less than two minutes. Moreover, it has a high-temperature range, namely between 0 °C and 300 °C. It is useful to have an idea about the sample flash point; this will help when setting the starting temperature for any sample. Choosing a starting temperature more than 40 °C than the essential flash point will result in getting No Flashpoint message on the LCD.

The embedded software has three modes of operation:

Manual: The temperature of the cup can be set to any value between 0 °C and

300 °C. The time allowed for the sample and vapour to reach equilibrium can be adjusted between 1 to 30 minutes.

Auto: Similar to manual mode, the temperature of the cup can fix any value between 0 °C and 300 °C. The time allowed for the sample and vapour to reach equilibrium set automatically. For temperature up to 100 °C, is set to one minute and for any temperature more than 100 °C two minutes. In addition to that, the tester required a 2ml sample.

Ramp: Likewise the previous modes, the temperature can be set to any value between 0 °C and 300 °C. In ramp case, the temperature increased at 2 °C/min to either 30 °C above the start temperature or until the flashpoint detected. In this mode, there is audible which prompts the operator to carry out the manual test after each one-degree rise in temperature or every two degrees in the case of temperature above 100 °C.

-

Testing Procedure:

- Before testing the samples, the tester checked. Part of that check was refilling the gas canister at the back of the tester. The gas canister was pulled to remove it after it was set off. It was refilled, from a butane refill cartridge. Then it was returned and switched on.
- The timer button was pressed and hold until a beep sound heard.

- The Ramp mode was chosen by rotating the adjustment knob.
- The temperature button was pressed and hold until a beep sound heard
- The Adjustment knob was rotated to choose the required temperature of this mode.
- After a period of stabilization, a beep sound heard. The tester is ready.
- The FD sample was loaded into the tester with the help of the 2ml syringe through the filling orifice.
- The Flame test jet and pilot jet was lightened using a match.
- The flame controlled through the white valve on the top of the tester.
- In this mode, the sample heated in increments of 1°C due to the temperature that was at 100 °C.
- After each beep, the shutter opened, and the Flame test lowered to check whether a flash point was reached.
- The above point repeated every 2 seconds.
- Flash detected and resulted shown on LCD.
- The test repeated in the same way for the rest of samples.

Appendix B

Engine Testing Operation Procedure (TOP)

PROCEDURE TITLE:		**Running LP460 engine and dynamometer**

RA REF:		SOP REF:	SOP.01

REASON FOR SOP *(tick all that apply)*:

X	Process/Procedure could cause significant injury *(over three day's absence)*.
X	Process/Procedure could cause occupational illness.
X	Process/Procedure could cause an environmental impact.
X	Process/Procedure could cause damage to property.

Completed by:	Abdelnasir Omran	Signature:		Date:	24/02/2017
Authorized by:	**Mr. David Smith**	Signature:		Date:	

LOCATION: This procedure may be performed at the following location(s).

L36, engine L460

DESCRIPTION OF THE PROCEDURE:

Time(s) of Work:	09.00 am – 16.00 pm
Individuals Involved:	All operators
Equipment and Materials Involved:	Water pump, exhaust extractions, engine LP460, and dynamometer.
Personal Protective Equipment Required:	Safety Goggles. Mechanical protection gloves. High-Safety shoes. Laboratory coats.

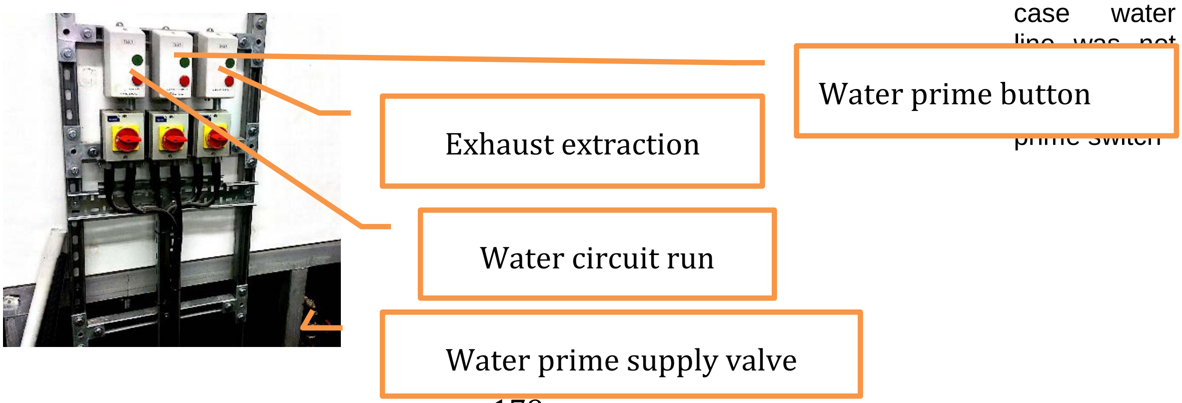
Job Step	Potential Hazards	Precautions
Make sure that all the personal protective equipment are present.	Don't have all the PPE	Request all PPE beforehand
Make sure that experienced staff or students have trained necessary training.	Risks the whole lab	Induction on the lab and engine testing
Switch on the light in the testing area (figure 1) and LP 460 engine cabin (Figure 2)	No sufficient light	Other light in lab switch by movement sensors

Figure 1: Engine area lights switches Figure 2: Engine cabin light switch

Initial steps:

1. Prime the water circuit which feeds the dynamometer by switching the key and press start (Figure 3). Then switch it off after around two minutes and switch on the run key.

Induction- water prime supply valve should be operated by staff only, in case water



Job Step	Potential Hazards	Precautions

Figure 3:

2. Check engine, fuels line, electric circuit, dynamometer, and shaft. If satisfied, go to the next step.

Start engine

1. Rotate dynamometer rotor wheel left and right, Shaft and load valve to make sure it is not stuck (figure 4)

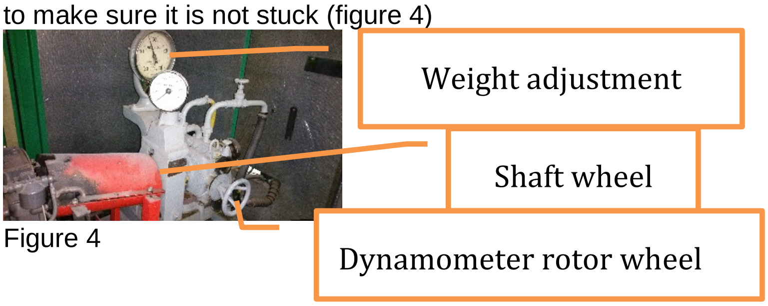


Figure 4

2. Try to bleed air out of the fuel line by pressing the bleed key in figure 4 many time. If it does not help fix the problem, disconnect the injectors bleed line (figure 4) and connect it again after making sure no more air in the fuel line.

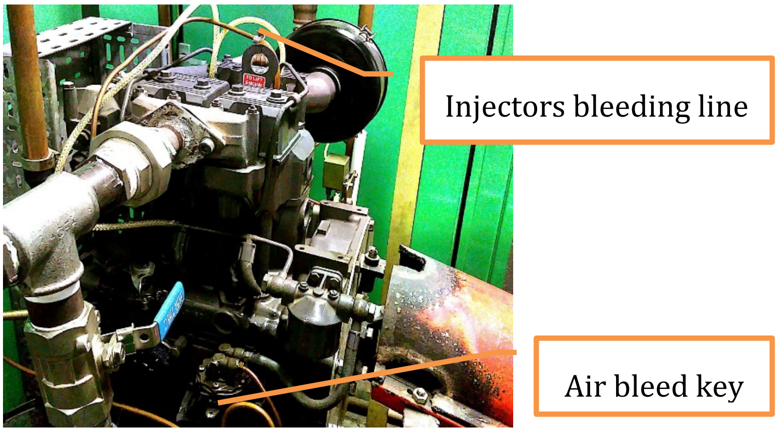
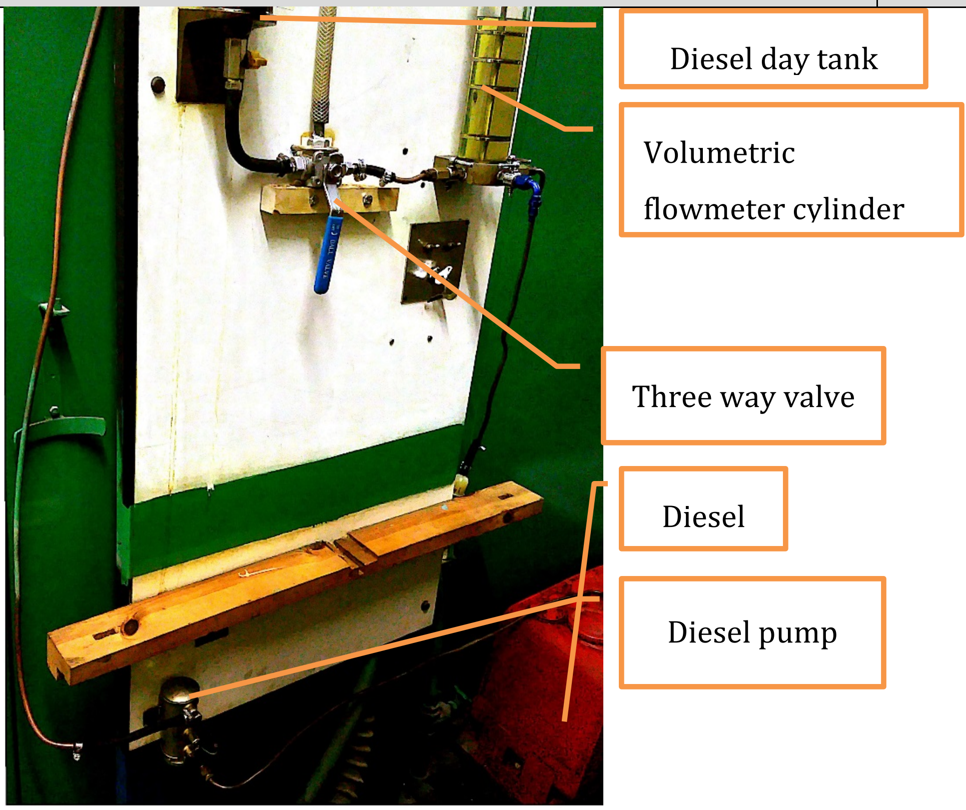


Figure 4

3. Close all cabin's doors.

4. Make sure the day fuel take is ¾ full using the fuel pump (Figure 5).

Job Step	Potential Hazards	Precautions



5. Make sure that the three-way valve is horizontal, open the day take valve and the volumetric flowmeter cylinder valves (Figure 5).
6. Make sure that the engine emergency key in not pulled off (Figure 6)

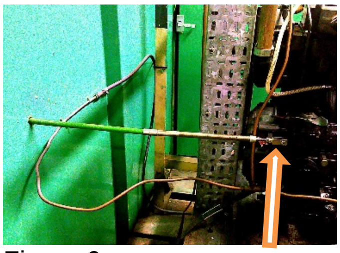


Figure 6:

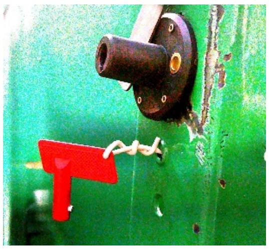
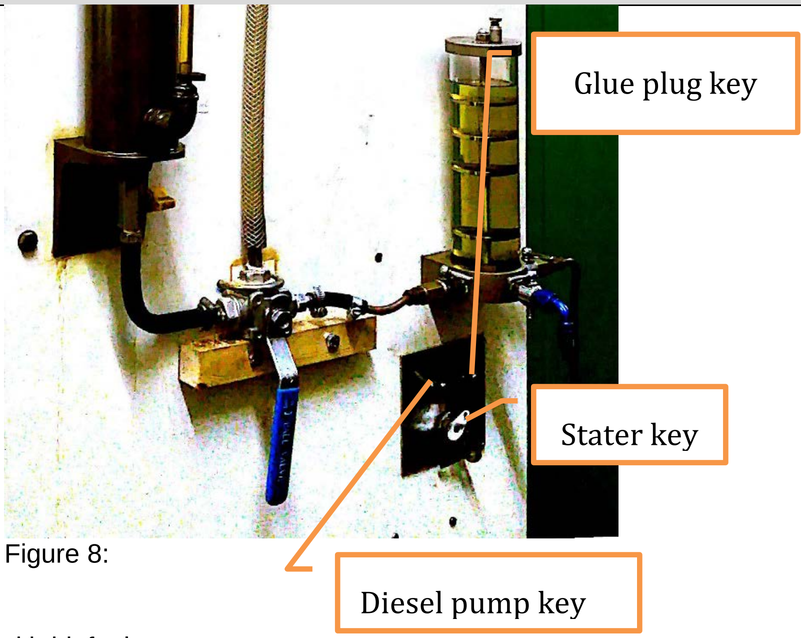
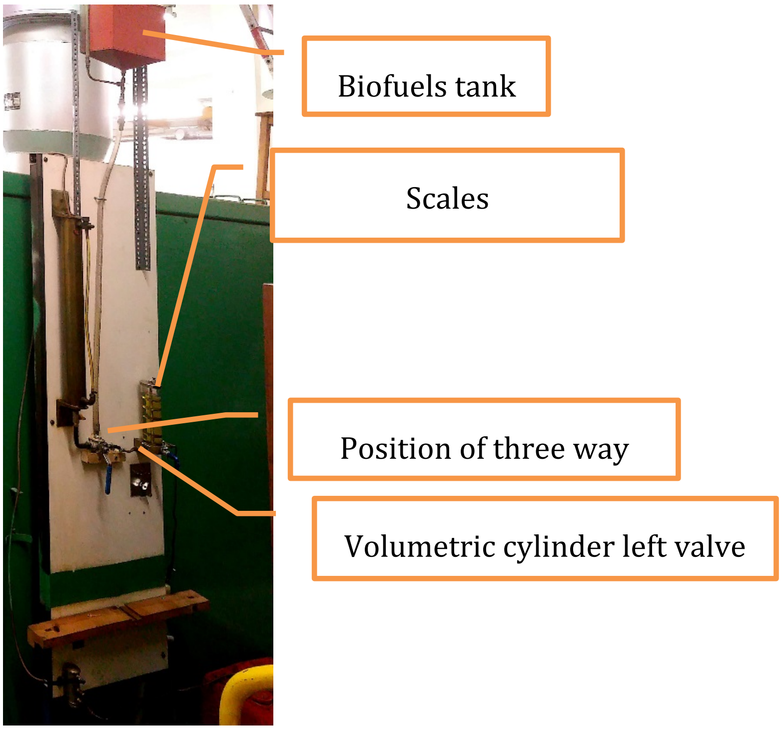


Figure 7:

7. Switch the electrical circuit on by putting the key in the holder and move it on (Figure 7).
8. Press the plugs glue key down for three seconds the let go and switch the start key (Figure 8).
9. Let the engine start and shut off for ten minutes before and after running with biofuels.

Job Step	Potential Hazards	Precautions
 Figure 8:		
Engine run with biofuels 1. Follow all the above steps but in step (5) close diesel day tank valve and move the three-way valve vertically up in line with the pipe coming from biofuels tank (Figure 9)  Figure 9:	Overfilling day tank	Visible level indicator installed
Measuring fuels consumption		

Job Step	Potential Hazards	Precautions

1. Close volumetric cylinder left valve and using stopwatch measure the time fuels take between any two scale points (Figure 9).

Using Froude water brake dynamometer

1. Torque is developed on the input shaft due to the toroidal vortices.
2. In the dyno, this torque is balanced by a set of weights that are hung a set distance from the center of the shaft.
3. This set distance is known, and therefore torque will be equal to the product of the weights and distance perpendicular to the axis.
4. To make sure that the weight is normal to the shaft axis, adjust the weight (Figure 4) until the two pointers on the back of the dyno match up.

5. Take the reading from the large dial gauge (lb).
6. The power can be calculated as follow:
7. Power (bhp) = WN/4500
8. W is the weight applied (large dial).
9. N is the engine speed in rpm (torque dial).

Job Step	Potential Hazards	Precautions
Measuring exhaust emission 1. Using Bosch BEA850 emissions analyzer should be through the dyno door to avoid any smoke flow to the lab and activate the fire alarm (figures 10&11).	Activate alarm	No work can be carried out with smoke. Immediately terminate work and stop engine

Figure 10:

Figure 11:

Shut up phase:

1. Switch fuel to diesel for around 10 minutes.
2. Move the governor to the right to stop the engine.
3. Turn electrical circuit off and pull the key out.
4. Final check-up for the whole testing rig
5. Switch water run key off
6. Switch exhaust extraction off.
7. Put light off

Job Step	Potential Hazards	Precautions

Emergency Response (Accident/Injury/Damage/Fire)

Report to state, lab manager, and security.

Spillage & Waste Disposal Arrangements

Through L36 lab technician

Storage Requirements

To be arranged with supervisors
The arrangement is to be discussed with supervisors and lab technicians.

Transport Arrangements (where applicable)

To be arranged with supervisors.

EMERGENCY CONTACTS:

Name:	Dr. Hossain A.K.	**Telephone:**	0121204 3041

REVIEW:

Last Review Date:	28/02/2017	**Next Review Date:**	28/02/2018

This SOP **MUST** be trained out to all personnel involved in the procedure/process and records of training be maintained by the supervisor.

Engine Testing's Risk Assessment procedure (RA)

SCHOOL/DEPARTMENT:	Mechanical Engineering and Design, EAS	**Reference No.:**	01
MAIN RISK AREA/TOPIC:	L36/ Engine testing runs	**ASSESSOR(S)**	Abdelnasir Omran
ASSESSMENT DATE:	24/02/2017	**NEXT REVIEW DATE:**	February 2018

What are the hazards?	**Who might be harmed and how?**	**What is the current measurement?**	**Is anything else need to be done to manage this risk?**	**Action by whom?**	**Action by when?**	**Done**
Flooding	Operators, Staff, Students & Visitors/ Fall & slip Injury and property damage	Train students how to switch the two separated switches for prime and running water supply to a dynamometer.	Label the two switches.	A.O	27/02/2017	Done
Fuels leaks	Operators, Staff, Students Burn injury, Fire and property damage.	Fuels line and the pipe are appropriately sealed, engine emergency stop and electrical circuit breaker installed. Tanks filling indicator installed.	Check before the start, regular maintenance, observed during the test. Never run diesel pump and walk away.	A.O	27/02/2017	Ongoing
Hot exhaust pipe	Operators / Scalding	There is a distance between it and emission test pipe.	Measure emission through dynamometer door.	A.O	27/02/2017	Ongoing
Risk of entrapment due to rotating parts	Operators	Shaft, flywheel and other moving parts are covered. Control panel is outside the engine cabin.	Testing rig must be operated from outside through control panel	A.O	27/02/2017	Done
Electrical shock	Operators	Electrical circuit breaker switch installed, wires covered with PVC pipes and fuse box installed.	Observe wires and connection before and during the run.	A.O	27/02/2017	Ongoing

	YES	NO
Does this risk assessment require the development of a Safe Operating Procedure?	X	
If NO, give a reason?		

AUTHORISATION AND SIGN-OFF

This risk assessment is suitable and sufficient.

ADDITIONAL COMMENTS:							
NAME:		**POSITION:**		**SIGNATURE:**		**DATE:**	

List of Publications

Journal Papers:

1. Hossain, AK, Serrano, C, Brammer, J, Omran, A, Ahmed, F, Smith, DI & Davies, PA 2016, 'Combustion of fuel blends containing digestate pyrolysis oil in a multi-cylinder compression ignition engine' *Fuel*, vol. 171, pp. 18-28. DOI:10.1016/j.fuel.2015.12.012

Conference papers:

1. Hossain, A, Nyah, J, Ahmad, A, Omran, A & Davies, P 2016, Experimental investigation of the fuel properties of glidfuel, palm oil mill effluent biodiesel and blends. in*Chemical engineering transactions.*Chemical Engineering Transactions, vol. 50, AIDIC, pp. 361-366. DOI:10.3303/CET1650061

Submitted journal paper:

1. **Physio-Chemical Properties of Plant-Based Oils for Energy generation in Sudan**

   Abdelnasir Omran*, Abul Hossain, Philip Davies, Refahtalab Pedram, Masera Kemal

   Sustainable Environment Research Group (SERG), Aston University, Birmingham B4 7ET, UK

   omrana@aston.ac.uk

Proposed journal papers:

1. Omran, A, Hossain, AK, Davies, P, Smith, D, Masera, K, Refahtalab, P;

   Use of Cottonseed oil and Castor oil for small-scale electricity generation in Sudan.

2. Omran, A, Hossain, AK, Davies, P, Smith, D, Masera, K, Refahtalab, P;

   Use of Jatropha oil for small-scale electricity generation in Sudan.