Croton megalocarpus oil-fired micro-trigeneration prototype for remote and self-contained applications: experimental assessment of its performance and gaseous and particulate emissions

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According to the International Energy Agency’s World Energy Outlook 2011, 60 per cent of the population in Africa, some 587 million people, mostly in sub-Saharan Africa, lacked access to electricity in 2009. We developed a 6.5 kWe micro-trigeneration prototype, on the basis of internal combustion engine with pure Croton megalocarpus oil (CMO) fuelling, which configures a distributed energy system to generate power, heating and cooling from a single sustainable fuel source for remote users. Croton megalocarpus is an indigenous tree in East and South Africa which has recently attracted lots of interests as a biofuel source because of its high oil-yield rate. The direct and local use of CMO, instead of CMO biodiesel converted by the transesterification process, minimizes the carbon footprints left behind because of the simple fuel production of CMO. The experimental assessment proves that the prototype fuelled with CMO achieves similar efficiency as with diesel. Also, with the elevation of the oil injection temperature, the gaseous and particulate emissions of CMO could be ameliorated to some extent as improvement of the atomization in the spray and the combustion in the engine cylinder.

1. Introduction

Access to energy services is crucial to meet basic household needs, deliver and access public services, and generate income. But less than 12 per cent of sub-Saharan rural households have access to electricity, with an overall access rate below 31 per cent. According to the International Energy Agency’s World Energy Outlook 2011, 60 per cent of the population in Africa, some 587 million people living in energy poverty, lacked access to electricity in 2009 [1]. Supported by some international organizations, various distributed energy technologies have been tried in the area, like windmills, water mills, solar panels, geothermal sources and biomass furnaces. Most of them are just simply too expensive for people to sustain, as they are still exorbitant for developed countries. In reality, sub-Saharan Africa is still heavily dependent on wood fuel and other biomass resources, which together account for 68 per cent of the total energy consumption in Kenya [2].

The potential solution to electrify Africa still largely depends on biofuels, because of the copious supply of biofuel resources in this continent and the affordable price of their application. In the last couple of decades, because of the diminishing potential of petroleum reserves, biofuel resources have been extensively explored through research and commercial developments, which aim to source biofuels to substitute, or partly replace, fossil fuels on a very large scale—for instance, fuels for cars. In Europe, rapeseed and sunflower are mainly used for biodiesel production, while in North and South America, rape-seed and soya beans are identified as the sources for biodiesel. But people soon...
realized the impacts of biofuels from the food crops on food security and the world market, and therefore started to shift to inedible biofuel resources. Jatropha is becoming popular in Asia and Africa and some efforts are being made for others, like algae. In sub-Saharan Africa, *Croton megalocarpus* oil (CMO) is a newly emerged option for biofuel production which has drawn a lot of attention recently.

*Croton megalocarpus* is a widely spread, indigenous tree in East and South Africa. Its bark has long been used as a source of medicine, and also as poultry feed, owing to the high protein content within the seeds. Recently, it was identified as a biofuel resource. Aliyu *et al.* [3] carried out a very detailed study on CMO seeds, and reported the annual seed yield per tree in the order of 25–40 kg and an average composition of 30–32% oil and 18–50% protein from a seed sample. Via oil extraction using both physical and chemical methods and a study of the properties of CMO, they pointed out that there were no operational problems for use as a fuel in the raw state in diesel engines, although it is normally subjected to a process of transesterification to remove glycerides. In Waguta *et al.*’s [2] research, they verified the potential of biodiesel production from CMO and compared it with another three types of indigenous plants, including Jatropha curcas in Kenya. The yield rate of *Croton megalocarpus* methyl ester (CMME) from CMO is 94.2 per cent, higher than that of 90.7 per cent from Jatropha curcas oil. They also examined the kinematic viscosity of CMME, which compared well with that of diesel. Other works have been done comparing potential plant oils in Africa. Kibazobu & Sangwan [4] compared five different species of potential biofuel plants for raw oil production. It was concluded that all varieties have an oil content from 20% to 33% w/w and seed/nut acreage yield of 3–12.5 t ha⁻¹ yr⁻¹. Among them, CMO has the highest raw oil production potential of 1.8 t ha⁻¹ yr⁻¹ compared with 1 t ha⁻¹ yr⁻¹ of *Jatropha curcas*.

With CMO being identified as a promising biofuel source in Africa, more researchers started to investigate the conversion process from raw oil to biodiesel. Kafuku *et al.* [5] and Mbarawa [6] optimized the CMME production process parameters experimentally. The optimum biodiesel conversion efficiency they obtained was 88 per cent at the optimal conditions of 1 wt% potassium hydroxide catalyst, 30 wt% methanol, 60°C reaction temperature, 400 r.p.m. agitation rate and 60 min reaction time. Another study [7] set similar conversion process parameters to produce biodiesel from CMO and checked the properties of CMME from the transesterification process. It was noticed that the oxidation stability of pure CMME was 2.88 h, lower than that of CMO (3.12 h). Thus, CMME did not meet the international oxidative stability requirements, which prescribe a minimum of 3 h for the ASTM D6751 standard and 6 h for the EN 14214 standard for biodiesels. Kivevele *et al.* [8] continued to investigate three antioxidants to ameliorate the stability of oxidation of CMME in their next paper. Kafuku *et al.* [5] introduced another method to produce CMME, which used sulfated tin oxide enhanced with SiO₂ as a solid superacid catalyst. The reaction parameters in the study are: 180°C, 2 h and 15 : 1 methanol-to-oil molar ratio, while keeping constant catalyst concentration of 3 wt% and stirring speed at 350–360 r.p.m.

It is quite obvious that a large amount of energy is consumed in the transesterification process or in any other means of biodiesel production from raw CMO in the earlier-mentioned literature. So, many researchers raised the question whether biodiesels are a sustainable substitute for fossil fuels. In most cases, the biofuel plants growing in developing countries are pre-treated on-site, and then transported to biofuel refineries to produce commercial products. The transportation of the feedstock, the final products and the biofuel production process are the vulnerable links that make biodiesel far from a carbon-neutral and sustainable fuel. Esteban *et al.* [9] did a comparative life-cycle assessment study on small-scale pure rapeseed oil and industrial biodiesel as truck fuel. The result revealed that the energy conversion ratio of rapeseed oil was 2.34, while that of biodiesel was 1.77. Similarly, in Yee *et al.*’s work [10], the energyconversion ratios of palm biodiesel and rapeseed biodiesel were 3.53 and 1.44. However, in Chen & Chen’s study [11], for the situation in China the overall energy input of rapeseed biodiesel was estimated at 1.1 times its biodiesel energy output; although they considered waste-water treatment, it was not always taken into account in other literature, along with agricultural production, transport and the transesterification process. Another life-cycle analysis also concluded a net negative energy return with biodiesel application. In this study [12], the total primary energy required for production of 1 MJ of fossil diesel energy is 1.20 MJ, which corresponds to a life cycle output-to-input energy ratio of 0.83. As for biodiesels, the energy ratio depends on species, local climate conditions, type and efficiency of agricultural machinery, mode of transport and conversion processing technologies. If soybean biodiesel in America is taken as an example [13], the primary energy requirement for 1 MJ of biodiesel production is 1.24 MJ; this corresponds to a life cycle energy ratio of 0.80. More importantly, nearly 87 per cent of the total primary energy requirement is used for converting soybean oil to biodiesel. By contrast, the primary energy requirement for 1 MJ of pure soybean oil production is only 0.161 MJ. Although there are no data available for CMO, it is believed that the energy conversion ratio of CMO must be much higher than that of its biodiesel.

Until recently, there was no literature covering the direct use of CMO on any engine, although in some available literatures, people tried CMME or a small portion of CMO in CMO/diesel blends on internal combustion engines and studied performance and emissions with these fuels. Firstly, Lujaji *et al.* [14] investigated the cetane number of CMO, 1-butanol and a diesel blend in a 10, 10 and 80 per cent ratio. Furthermore, they did the performance comparison with different blends in a compression ignition (CI) engine [15]. The blends they tried included 20 per cent CMO–80 per cent diesel, 15 per cent CMO–5 per cent 1-butanol–80 per cent diesel and 10 per cent CMO–10 per cent 1-butanol–80 per cent diesel and with 100 per cent diesel as baseline. They noticed the benefit of adding butanol to the blends, so only compared 15 per cent CMO–5 per cent 1-butanol–80 per cent diesel and 10 per cent CMO–10 per cent 1-butanol–80 per cent diesel in the next paper [16]. It concluded that butanol alcohol in the blends resulted in increased brake-specific energy consumption (BSEC) at higher engine loads and caused brake thermal efficiency (BTE) to decrease. Blends resulted in the reduction of emissions, while CO₂ and smoke levels at high loads were reduced, NOₓ (NO and NO₂) emission levels were similar to that of the diesel. Aliyu *et al.* [17] conducted a performance and exhaust emission research on a diesel engine with pure CMME (B100) and various blends with diesel.
In the experiments, BTE decreased with the increase in the percentage of CMME in the blends associated with an increase in BSEC. In comparison with diesel, CO, CO₂ and hydrocarbon (HC) emissions were higher for CMME blends but had lower smoke emission. Kiveele et al. [18] continued to conduct tests on diesel engines with CMME dosed with synthetic antioxidants (B100 + antioxidant 1000 ppm) and compared with other fuels, including CMME (B100), CMME/diesel blend (B20) and pure diesel. Similar findings on brake-specific fuel consumption and BTE were concluded, but for HC, emissions were found to be reduced at intermediate and full load for CMME while NOx was always higher than that of diesel. The above publications verified the possibility to apply CMO on existing CI engines with different methods, including converting to CMME by transesterification process, blending with diesel or some additives in various percentages, etc. However, there is one way yet to be tried, which is to apply CMO directly on engines. It will dramatically boost the life-cycle output to input-energy ratio in terms of the earlier-mentioned discussion.

This is not a new concept of pure plant oil fuelling for internal combustion engines, because extensive reviews have been done in depth. Back to 2004, Ramadhas et al. [19] did a comprehensive review of all the research that had been done with vegetable oils as fuel at that time. Major foodcrop-derived oils and their methyl esters (biodiesels), such as sunflower, soybean, and rapeseed, were investigated. Since then, increasing numbers of pure plant oil applications have been reported and a comprehensive review by Hossian & Davis [13] in 2008, in which they concluded that BSFC of pure plant oils is generally greater than that of diesel, and, in turn, the BTE of pure plant oils is in the range of +3 to −10% compared with fossil fuels. In 2010, a review mainly covering the situation in India was carried out by Misra & Murthy [20]. On the basis of the review of international and Indian research a SWOT analysis was done, and, from it, they pointed out that preheating of the fuel by exhaust gases could be one feasible solution to overcome the problem of high viscosity—being the major cause of many problems for pure plant oil application on engines. A review dedicated to crude filtered vegetable oil as fuel was carried out by Sidibe et al. [21], which underlines pure vegetable oil quality in association with processing parameters and storage conditions. Two types of pure vegetable oil use in diesel engines, dual fuelling (start-up with diesel and transfer to vegetable oil) and pure vegetable oil/diesel blends were discussed, which concluded either upstream adaptations (dual fuelling, blending, preheating) or modifications on engine (fuel pump, fuel filter, injector and piston) needed. A more recent review by Soo-Young No [22] focused on inedible vegetable oils and their derivatives using CI engines. Seven different kinds of inedible vegetable oils, including Jatropha, are reviewed, according to various ways to apply them in engines. The performance of Jatropha oil in dual-fuel operation revealed that HC, CO and NOx emissions were higher and the smoke level lower than diesel. In his paper, Soo-Young No still recommended fuel modification via blending, pyrolysis, microemulsion, transesterification and hydrodeoxygenation to reduce polymerization and viscosity. It was also mentioned that most pure vegetable oil use is limited to single cylinder engines.

As CMO can be produced locally on a small scale by cold compression, the seed meal after the oil extraction process is still of some use. Aliyu et al. [3] indicated that the croton tree was a subject of interest as a source of animal feed because of its non-toxicity and high protein content in the seeds. The idea could be dated back to 1990s, when Thijissen [23] tried to explore the possibility of using CMO for poultry feed. Croton seed has been identified as a good protein supplement for birds, which they cannot synthesize by themselves. In the study, it was estimated that if the 60 000 croton trees in the Embu District of Kenya yielded only 20 kg of seeds per tree, every child in that area would be assured of eating at least 200 eggs per year if the croton seeds formed 50 per cent of the diet of chicken. Although only 70 per cent mass weight of seed meal after the oil extraction was left, the croton seed meal still can substitute a substantial percentage of poultry feed locally. More importantly, there is no need for any after-treatment of the CMO by-product; instead, the CMO production process could be integrated with poultry feed production.

With comprehensive understanding of the context of pure plant oil applications, generally plant oil is a sustainable fuel compatible with CI engines and much closer to the carbon-neutral concept than any other biofuels and fossil fuels. Therefore, it is promising that pure CMO can be used locally to cope with the electrification issue in sub-Saharan Africa. Some data from commercial companies relating to back-up generators support the point that their small-scale diesel engine-generator products meet up to 50 per cent of Uganda’s power needs, and 10 per cent of those of Kenya and Tanzania. In this paper, the authors are aiming to develop a low-cost, small-scale, pure CMO-fired engine generator, and, for maximizing the energy utilization efficiency, further modify it to a trigeneration system with coolant and exhaust heat recovery and an absorption cooling option, which is tailored for solving the electrification issue in Africa. The experimental study via trigeneration performance and emission tests on both pure CMO and diesel is trying to fill the gap of direct use of CMO for electricity generation in remote contexts. Both fuel and engine modification will be made in a cost- and energy-effective way to prevent the problems caused by pure plant oil fuelling, but still maintain the overall cost of the prototype at a affordable scale. The emissions are investigated carefully as potential health and environment hazards must be ruled out for a distributed energy system located in residential areas and even in remote rural areas.

2. Composition and properties of Croton megalocarpus oil
The CMO applied to the CI engine was shipped from Africa after it had gone through the simplest cold-pressed process and filtration. The physically extracted oil preserves the original composition without any other chemical additives. The filtration process ensures that the oil is free of any solid impurities, such as seed husks, etc. Gas chromatography has been carried out on the croton oil. The fatty acid compositions of the raw croton oil are presented in table 1. The CMO mainly contains unsaturated fatty acids, including oleic, linoleic and linolenic acids, which all together account for 87 wt% (see electronic supplementary material, FAME). The other major saturated fatty acids that are common in plant oils are palmitic and stearic acids. It has been observed that CMO contains the highest linoleic acid (C18-2) weight
percentage of 74.31 per cent among various raw plant oils. This might be the reason for its relatively low viscosity compared with other pure plant oils at the same temperature. It has been reported [24,25] that soybean biodiesels derived from an oil high in oleic acid and low in saturated fatty acids could potentially improve oxidative stability while augmenting cold flow; it has yet to be proven whether this is the case for CMO.

Table 1. Comparison of the fatty acid compositions of the plant oils (wt%).

<table>
<thead>
<tr>
<th>fatty acids</th>
<th>Croton</th>
<th>sunflower</th>
<th>rapeseed</th>
<th>Jatropha</th>
</tr>
</thead>
<tbody>
<tr>
<td>lauric acid (C12:0)</td>
<td>0.11</td>
<td>0.11</td>
<td>0.04</td>
<td>0.14</td>
</tr>
<tr>
<td>myristic acid (C14:0)</td>
<td>0.04</td>
<td>0.16</td>
<td>0.04</td>
<td>0.11</td>
</tr>
<tr>
<td>palmitic acid (C16:0)</td>
<td>6.23</td>
<td>6.47</td>
<td>4.96</td>
<td>16.64</td>
</tr>
<tr>
<td>palmitoleic acid (C16:1)</td>
<td>0.11</td>
<td>0.10</td>
<td>0.32</td>
<td>1.18</td>
</tr>
<tr>
<td>stearic acid (C18:0)</td>
<td>4.37</td>
<td>4.34</td>
<td>1.73</td>
<td>5.94</td>
</tr>
<tr>
<td>oleic acid (C18:1)</td>
<td>9.95</td>
<td>24.59</td>
<td>62.07</td>
<td>37.25</td>
</tr>
<tr>
<td>linoleic acid (C18:2)</td>
<td>74.31</td>
<td>62.68</td>
<td>19.16</td>
<td>38.03</td>
</tr>
<tr>
<td>linolenic acid (C18:3)</td>
<td>3.62</td>
<td>0.44</td>
<td>9.63</td>
<td>0.25</td>
</tr>
<tr>
<td>arachidic acid (C20:0)</td>
<td>0.92</td>
<td>0.40</td>
<td>1.49</td>
<td>0.46</td>
</tr>
<tr>
<td>Erucic acid (C22:1)</td>
<td>0.33</td>
<td>0.71</td>
<td>0.53</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2. Properties of diesel, CMO and rapeseed oil (DIN 51605).

<table>
<thead>
<tr>
<th>element composition (wt%)</th>
<th>diesel a</th>
<th>CMO</th>
<th>DIN 51605 method</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>87</td>
<td>76.9</td>
<td>—</td>
</tr>
<tr>
<td>H</td>
<td>12.6</td>
<td>11.6</td>
<td>—</td>
</tr>
<tr>
<td>O</td>
<td>0.4</td>
<td>11.5</td>
<td>—</td>
</tr>
<tr>
<td>molar mass (kg kmol⁻¹)</td>
<td>190</td>
<td>279</td>
<td>—</td>
</tr>
<tr>
<td>density (kg m⁻³) at 15 °C</td>
<td>830</td>
<td>917.3</td>
<td>910–925 ASTM D1289</td>
</tr>
<tr>
<td>dynamic viscosity (mPa s) at 40 °C</td>
<td>2.4</td>
<td>25.7</td>
<td>—</td>
</tr>
<tr>
<td>kinematic viscosity (mm² s⁻¹) at 40 °C</td>
<td>2.5</td>
<td>28</td>
<td>&lt;36 ASTM D445</td>
</tr>
<tr>
<td>low calorific value (MJ kg⁻¹)</td>
<td>42.5</td>
<td>37.24</td>
<td>&gt;36 ASTM D240</td>
</tr>
<tr>
<td>Cetane number</td>
<td>48</td>
<td>40.7</td>
<td>—</td>
</tr>
<tr>
<td>Iodine value (g 100 g⁻¹)</td>
<td>133 [2]</td>
<td>&lt;125</td>
<td>—</td>
</tr>
<tr>
<td>Acid value (mg KOH g⁻¹)</td>
<td>0</td>
<td>1.7 [2]</td>
<td>&lt;2.0</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>75</td>
<td>&gt;192 [7]</td>
<td>&gt;101</td>
</tr>
<tr>
<td>Oxidation stability (h) at 110 °C</td>
<td>3.12 [7]</td>
<td>&gt;6</td>
<td></td>
</tr>
</tbody>
</table>

a diesel = industry gas oil—BS2869:2006 class D.

The German standard—DIN 51605—is the first standard for testing of rapeseed oil used as fuel for vegetable oil-compatible combustion engines, and established standards for some important parameters. Similar tests of CMO have been done via various standard methods in the chemistry laboratory and are presented and compared with diesel and rapeseed oil standards in table 2. The element mass composition shows that, similar to other biofuels, CMO has a high oxygen content, which is crucial to the result of the emission tests. The lower calorific value indicates that more CMO is needed to achieve the same engine load. But with the high density of CMO, only a slight increase in the volume consumption of CMO compared with that of diesel is expected. The viscosity of CMO and that of other plant oils is much higher than that of diesel, normally more than 10 times at a temperature of 40 °C. However, temperature has a critical impact on viscosity: the higher the temperature the lower the viscosity. CMO has been tested in different temperatures, ranging from 20 °C to 120 °C (see electronic supplementary material, Vegetable oil viscosities). The results of CMO, diesel and several other plant oils are shown in figure 1. After reaching 90–100 °C, the viscosity of CMO is very close to that of diesel in ambient temperature, and therefore the CMO could be preheated up to about 90 °C before injection to minimize the adverse impact of high viscosity on engine performance.

3. Materials and methods

In order to carry out the experiments on a CMO-fired micro-trigeneration system, a small one-cylinder CI engine model was selected as the prime mover, namely a Yanmar TF120 M.
The particulates in engine exhaust gas, and counts only the solid particle. The equipment is compliant with the particle quantity measurement method recommended by the revision (ECE/TRANS/WP.29/GRPE/2008) of ECE regulation R83. The detector of the Horiba MEXA-1000SPCS can measure particulates from 23 nm to 2.5 μm. The particulate mass is measured by the TEOM Series 1000 particulate monitor, which takes sample from the exhaust pipe with a 0.42 s sampling period. The measurement principle is based on the relationship between the tube oscillation frequency change and the change of particulate mass blocked by the filter at the free end of the tube.

As the trigeneration system may work at a different partial load in terms of the user’s demand, the experiments were designated to be conducted at 10, 25, 50, 75 and 100 per cent of the genset’s rated power output. The engine speed was maintained at 2400 r.p.m. during the tests. At each testing point, the trigeneration system ran for at least half an hour at the testing condition to achieve steady working of the engine before any measurement commenced. Continuous measurement included recording temperatures, flow rates, pressures, currents, voltages, engine speed, etc., and a Siemens control and data logging system automatically recorded the data and did the basic calculations, such as the quantity of heat, cooling and power produced by the trigeneration system. Three emission analysers took at least five sample periods during measurement, and the exact time was logged for matching the other data from the Siemens system. Finally, the experiments at each testing point were repeated several times at similar ambient conditions. In the experiments, three fuels were tried, namely diesel (gas oil, class D) without preheating, CMO with preheating to 60°C, and CMO with preheating to 90°C. The fuel temperature at the free end of the test point, which is just before the fuel injection pump, were kept within ±0.5°C of the testing temperatures.

Figure 1. Dynamic viscosity comparison among different fuels.

(Bore: 92 mm; stroke 96 mm; displacement: 0.638l; rated continuous output: 7.8 kW at 2400 r.p.m.; compression ratio: 17.7; injection timing: bTDC 11.5; injection pressure: 200 kg cm⁻²) (figure 2). The engine links to the AC generator via a belt, and the genset can produce a maximum of 6.5 kWe power. As the stationary engine works, it needs to maintain a constant speed (2400 r.p.m.) to keep the frequency of electricity at 50 Hz. Some modification in the fuel line system has been done for applying CMO directly, including the oil heat exchangers, the trace heater, the temperature controller, the extra filter with check valve, etc. The ultimate goal is to keep the temperature of the fuel exact before the fuel injection pump and prevent any clogging of the pumps and the injector.

The engine coolant and exhaust system has been modified as well to configure a trigeneration system (figure 3). The jacket water is introduced to go through the coolant water heat exchanger, which is placed in parallel with the oil heat exchanger. The secondary water circuit of the coolant water heat exchanger comes from the water storage tank, and after going through the coolant water heat exchanger, it enters the exhaust heat exchanger for the next stage heat recovery before it goes back to the water storage tank. The engine exhaust pipe has been split into three exhaust branches, which are all controlled by the proportional open/close gas valves. In the first branch, as mentioned already, there is an exhaust heat exchanger for recovering a large amount of heat, potentially for space heating or domestic hot water. The second branch leads to the diffusion absorption fridge/freezer, which uses the heat from the exhaust to drive the ammonia/water absorption cooling cycle and consequently produce cooling for food storage. At the last exhaust branch, an experimental phase change material (PCM) heat storage unit uses the exhaust gas heat stored during the last engine run to heat the plant oil in the engine cold start, which is expected to replace the electric trace heater eventually.

A sensor hole has been drilled just after the engine cylinder exhaust outlet, which is also split into three small sample pipes linking with three emission analysers: Horiba MEXA-1600, Horiba MEXA-1000SPCS and TEOM Series, which sample gaseous emissions, particulate number and particulate mass weight respectively during the trigeneration system operation. The Horiba MEXA-1600 is equipped with analyser modules compliant with ISO-8178 for measuring CO, CO₂, O₂, NO, and total HC in volumetric concentration. The Horiba MEXA-1000SPCS removes volatile particles from the particulates in engine exhaust gas, and counts only...
4. Results and discussion

4.1. Performance

The BSFC of diesel and preheated CMOs are determined from the measured results and plotted against power output percentage in figure 4. It was noticed that the CMO consumption was generally higher than that of diesel. At 100 per cent load, the BSFC of CMO reaches about 0.365 kg kWh$^{-1}$, which is about 20 per cent higher than that of diesel, owing to the lower calorific value of CMO (see electronic supplementary material, CMO_GO_Performance). Compared with the BSFC of other pure plant oils, the BSFC of CMO is slightly higher, because the power output used here is the electric power instead of the mechanic power. Therefore, the electric efficiency of the generator needs to be considered. As the injection pressure of 200 kg cm$^{-2}$ is not changed during the test, only the injection temperature is changed, no significant BSFC change can be observed for the same fuel when the injection temperature is elevated. No reference about CMO is available, but some experiments on CMME could provide some idea about energy consumption comparison. Aliyu et al. [17] tested five modes of CI engine on both diesel and pure CMME. In mode 1 of full load, the BSFCs of CMME and diesel were about 0.210 kg kWh$^{-1}$ and 0.170 kg kWh$^{-1}$. The lower BSFC attributed to the relative large CI engine they chose (33.56 kW output, three cylinder direct injection engine) and the higher calorific value of CMME (40.28 MJ kg$^{-1}$) compared with that of CMO (37.24 MJ kg$^{-1}$). In Kivevele et al.’s study [18], the BSFC of diesel (0.225 kg kWh$^{-1}$) was 14 per cent lower than that of pure CMME (0.265 kg kWh$^{-1}$). They also chose a larger engine with 66 kW output at 4000 r.p.m. In Lujaji’s works [15,16], a small percentage of CMO was blended with diesel; therefore no significant changes to BSEC were found in the results. Although he did not try pure CMO, the calorific value of CMO of 36.98 MJ kg$^{-1}$ is very close to the test result of this study.

As we built the trigeneration for electricity generation, no dynamometer was applied in the test rig. The electricity generation efficiency (EGE), instead of BTE, was recorded versus different loads. Still, it is an important index for trigeneration systems, considering that the generator efficiency is in the range of 80–90%. Unlike the engines for automobiles, the Yanmar engine in the trigeneration system is linked up with the generator via the belt for electricity generation at a constant speed of 2400 r.p.m., even in partial load conditions. Because the BTE of the engine drops with decreasing power output, the trigeneration system is always expected to run on full capacity instead of low partial loads. While running on diesel, the EGE of the trigeneration is about 28.1–28.4%, which is quite high for a small CI engine. If the CMO is used, the EGE drops to about 26.3–26.6%, which is still acceptable, seen in figure 5. Preheating up to 60°C has no significant influence on the EGE. If the temperature of the CMO at injection reaches 90°C, the EGE decreases under some partial load running conditions. Kivevele et al. [18] and Lujaji et al. [15] used the same engine (Audi 1.9 L TDI, 66 kW 4000 r.p.m.) with pure CMME and then with 20 per cent CMO–80 per cent diesel. The BTE reaches a remarkable 39.085 per cent for 20 per cent CMO–80 per cent diesel, and 36.88 per cent for pure CMME.

In figure 6, the exhaust temperatures of diesel and CMO are shown under the different engine loads. The exhaust temperatures could vary from one running to another, but generally the elevated injection temperature of the fuels will lift the exhaust

In this study, the trigeneration system was used to generate heat and electricity, and the exhaust gases were used to preheat the biofuel. The trigeneration system includes a biofuel micro-trigeneration system and an energy storage system. The biofuel micro-trigeneration system includes a biodiesel engine, heat exchangers, electric heaters, and PCM storage. The energy storage system includes an absorption refrigerator and a space heater. The exhaust gases from the biodiesel engine are preheated using the heat exchangers and electric heaters. The preheated biofuel is then injected into the engine and ignited to produce electricity and heat. The exhaust gases from the engine are then used to preheat the biofuel again. The preheated biofuel is then injected into the engine again, and the process continues. This system is able to generate both electricity and heat, and the exhaust gases are used to improve the efficiency of the system.
temperature. In most cases, the exhaust temperature of the engine running on CMO is higher than that while running on diesel. The maximum exhaust temperature of the engine running on CMO could be up to 580°C, which indicates a relatively high late-burning combustion temperature in the cylinder. Owing to the longer ignition delay of CMO, a delay in late-burning combustion could happen, which in turn causes a high exhaust temperature and less energy converted into power when CMO combusts in the cylinder [26,27]. However, a higher exhaust temperature may not be a bad thing, especially for a trigeneration system, because potentially more heat could be recovered from exhaust and more importantly the higher the exhaust temperature is, the easier it would be for the exhaust heat to give the absorption refrigerator a kick to start the cooling cycle. In other literature, only Aliyu [17] mentioned that the highest exhaust temperature for his testing engine at the maximum power of 30 kW was 448°C when pure CMME was combusted.

The application of trigeneration in a remote context and self-contained mode makes the thermal heat recovery equally as important as electricity generation. At the engine’s full capacity, the performance of the trigeneration system has been investigated via an energy distribution audit in figure 7. For diesel, about 7.7 and 5.7 kW of heat can be recovered respectively from the coolant and the exhaust gas. As for CMO, the coolant heat recovered decreases to 6.7–6.9 kW, owing to its low heat release rate in the cylinder. Owing to the longer ignition delay of CMO, a delay in late-burning combustion could happen, which in turn causes a high exhaust temperature and less energy converted into power when CMO combusts in the cylinder [26,27]. However, a higher exhaust temperature may not be a bad thing, especially for a trigeneration system, because potentially more heat could be recovered from exhaust and more importantly the higher the exhaust temperature is, the easier it would be for the exhaust heat to give the absorption refrigerator a kick to start the cooling cycle. In other literature, only Aliyu [17] mentioned that the highest exhaust temperature for his testing engine at the maximum power of 30 kW was 448°C when pure CMME was combusted.

The result is similar to Aliyu et al.’s work [17], which applied pure CMME. A reasonable explanation is that a lower hydrogen/carbon ratio and higher fuel consumption due to the lower calorific value of biofuels consequently have an increase in CO2 emissions. Overall, with CMO local application, there would be massive CO2 reduction in the life cycle of the fuel.

In figure 10, NOx emissions of diesel and CMO at different engine loads are plotted. Under the lower loads, no large differences in NOx emissions were noticed, but the NOx of CMO increases and become slightly higher than that of diesel under higher loads. In general, the formation of NOx is affected by temperature and the local fuel–air ratio, more specifically the peak flame temperature, the high burning gas temperature, the ignition delay and the content of oxygen available during the reaction time. CMO has a high oxygen content, which may potentially assist the formation of more NOx. Ignition delay is a more important reason at lower partial loads, but is almost the same at the full load. Both CMO and diesel have the minimum CO emissions at 75 per cent engine load (see electronic supplementary material, CMO690_G030_GE), which is verified by Lujaji’s work [16], although he blended CMO in only small percentage into diesel. In his paper, it was also reported that high CO emissions were observed for lower loads, with the smallest emissions recorded at 75 per cent engine load. It could be interpreted that for lower loads, CO emissions are increased because of incomplete combustion with increasing amounts of CMO injected, whereas at 100 per cent load, CO emissions are increased because of the local presence of a richer mixture in the combustion chamber. But it was also noticed that the result shows an adverse trend in comparison with that of Aliyu et al.’s study [17], which was using pure CMME.

As the biofuel plants absorb CO2 during their growing periods, it is believed that the CO2 emitted from the combustion of biofuels is roughly the same as the CO2 absorbed. However, further processing and transportation of the biofuels add some CO2 emissions to the biofuel life cycle, which deprecates the biofuels as carbon-neutral fuel and still allows the positive net CO2 emission. Using pure plant oils locally like CMO means that the user could to a great extent decrease the CO2 emissions during life cycle of the biofuel. But it is still important to measure the direct CO2 emissions from the exhaust. The CO2 emissions generated with CMO and diesel at different engine loads are shown in figure 9. The CO2 of combusting CMO is continuously higher than that of diesel and increases with the load increase. The result is similar to Aliyu et al.’s work [17], which applied pure CMME. A reasonable explanation is that a lower hydrogen/carbon ratio and higher fuel consumption due to the lower calorific value of biofuels consequently have an increase in CO2 emissions. Overall, with CMO local application, there would be massive CO2 reduction in the life cycle of the fuel.

4.2 Gaseous emissions
The emissions of CO from trigeneration when fuelled with CMO and diesel are compared in figure 8. The CO from combusting CMO is about two times higher than that of diesel at
lower loads. The preheating of CMO could reduce the ignition delay time and in turn reduce NOx emission. At higher loads, the in-cylinder temperature becomes the dominant factor to determine NOx emissions. A similar trend of NOx was reported by Kivevele et al. [18] with pure CMME. However, in other studies, NOx reduction was reported [17].

Figure 11 shows the differences in total HC between diesel and CMO. The general reason for HC formation is that there is a poor fuel/air mixture to such a high extent that the ratio is past the combustion limit. CMO with high oxygen content may prevent a certain combustion limit being reached, but its high viscosity may have adverse impact on this. The higher total HC at low loads in figure 11 attributes to the poor atomization of CMO owing to its higher viscosity after the preheating. It is noticed that, at full load, CMO with preheating to 90°C starts to decrease total HC emissions. The in-cylinder temperature at high loads may play an important role in it, but the reason is yet to be confirmed.

4.3. Particulate emission

Some studies [28] found that the particulate matter (PM) 2.5-0.1 particulate samples are more toxic than the PM10-2.5 fraction, with doses similar to those reported in previous studies in polluted urban areas. The particulate emission
measurement setting in the study has removed all particulates larger than 2.5 μm (PM2.5). The major contribution of the particulate number comes from the nucleation mode (less than 100 nm) compared with the accumulation mode (100–900 nm) and the coarse mode (greater than 900 nm). The particulate numbers of different fuels in different loads have been recorded in figure 13. With preheating to 60°C, CMO applied to the engine show a significant boost in the number of the particulates compared with diesel. The still high viscosity is the main reason, which results in poor atomization and, in turn, causing the increasing formation of soot. When CMO is heated to 90°C, its viscosity is similar to that of diesel at 32°C. The atomization and the combustion condition in sequence have been improved, which depresses the formation of the soot. Aliyu et al. [17] and Kivevele et al. [18] only measured the smoke, which indicated that a massive reduction could be realized by blending CMO into diesel or applying CMME. Hossain & Davies [13] introduced the Sauter mean diameter of droplets, which verifies the importance of density, viscosity and surface tension in affecting the spray pattern during the injection system, and in turn affects the combustion of the plant oil inside the engine, and consequently has an impact on the particulate number of the exhaust.

The specific particulate mass versus the engine loads is shown in figure 13. The comparison is between diesel at 32°C and CMO heated to 90°C, which have similar total fine particulate numbers. The result indicates that the specific particulate mass of CMO is within the range 0.4–1.2 g kWh⁻¹ in various loads, which is similar to that of diesel, although the majority of the values for diesel are lower than 0.6 g kWh⁻¹. EU emission standards for on-site power generation have been applied. From 2012, all gensets have to meet Stage IIIA, which requires gensets in the range of 18–36 kW to emit PM less than 0.6 g kWh⁻¹ (http://www.dieselnet.com/standards/eu/nonroad.php#s3). But no compulsory requirement needs to be met for gensets smaller than 18 kW. In the USA, stricter regulation applies to gensets smaller than 8 kW, which is the Tier 4 emission standard. (http://www.dieselnet.com/standards/us/stationary.php). For capacities lower than 8 kW, the PM cannot exceed 0.4 g kWh⁻¹ for the Tier 4 standard. As for micro-trigeneration, it is designed to be a

Figure 11. Total HC emissions of diesel and CMO at different engine loads.

Figure 12. Fine particulate numbers of different fuels.

Figure 13. Specific particulate mass of different fuels.
distributed energy supply system and therefore will be located in residential areas. The emission of PM2.5 needs to be highly concerned. So the after-treatment is necessary. Diesel particulate filters or traps are highly commercialized products to capture particulate from the exhaust either by mechanical filters or by catalyst filters that provide periodic or continuous oxidation. The application of the preheated CMO can achieve equivalent performance and emission compared with diesel; thus, only small amendment of the engine after-treatment system is needed to meet the strictest emission standard.

5. Conclusions

This paper explores an alternative solution with pure plant oil fuelling microtrigeneration system to electrify the large remote area in Sub-Saharan Africa and change the energy poverty situation there, which could be taken as a new thinking of how to use a good biofuel source—CMO. Instead of being transported to bio-refinery to produce biodiesel for automobiles in developed countries, CMO could be better used with simple process, available technologies and less carbon footprint, to serve the local communities and people.

The pure plant oil fuelling micro trigeneration prototype runs well on either diesel (industrial gas oil) or pure CMO, which produces maximum 6.5 kW e power and roughly 13 kW thermal output in high efficiencies, 26.3–26.6% EGE for CMO and a total 76% per cent of prime energy efficiency. A family-size absorption refrigerator is driven by a small fraction of exhaust heat to add cooling option to users. With more than 200 h run on CMO, the performance of the system maintains the same. No deterioration of the engine has been detected yet with the help of fuel preheating and filtration before injection.

As CMO has never been used directly on CI engines, gaseous and particulate emissions are closely investigated for residential environment and human health concerns. CO and total HC emissions of CMO are higher than those of diesel, but they getting closer in high engine loads due to the preheating and the increased in-cylinder temperature. However, the in-cylinder temperature increase in high engine loads along with the high oxygen content within CMO also causes the increase of NOx from CMO combustion. Although CO2 emissions of CMO are always a bit higher than those of diesel, the simple production process, the elimination of transport and the pure plant oil fuelling make CMO a close carbon-neutral fuel from a life-cycle perspective.

The significant decrease of the amount of the particulates with the preheated croton oil reflects a big improvement of the atomization and combustion in the cylinder compared with the non-preheated CMO. The particulate emission mass concentration test reveals the similarity of the weights of the particulates emitted from the engine generator system running on the diesel and the preheated CMO. The emission tests verify the safety of CMO application on micro-trigeneration prototype.

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