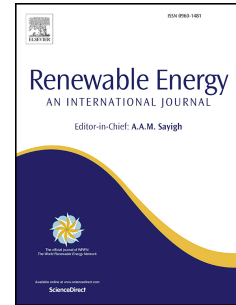


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Life-cycle assessment of self-generated electricity in Nigeria and Jatropha biodiesel as an alternative power fuel

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1 **Life-cycle Assessment of Self-Generated Electricity in Nigeria and Jatropha**

2 **Biodiesel as an Alternative Power Fuel**

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21 **ABSTRACT**

22 Insufficient available energy has limited the economic growth of Nigeria. The country suffers from frequent  
23 power outages, and inconvenient black-outs while residents and industries are forced to depend on self-  
24 generated electricity. Life-cycle assessment methodology was used to assess the environmental burdens  
25 associated with self-generated electricity (SGE) and proposed embedded power generation in Nigeria. The study  
26 shows that SGE from 5 kVA diesel generators contributes to greenhouse gas (GHG) emissions of 1625 kg CO<sub>2</sub>  
27 eq./MWh, along with other environmental burdens. Based on a point estimate of diesel electric generators in  
28 Nigeria, SGE can contribute 389 million tonnes CO<sub>2</sub> eq. to climate change every year. This can reposition  
29 Nigeria as one of the top 20 emitters of CO<sub>2</sub> globally. A mandatory diesel fuel displacement with *Jatropha*  
30 biodiesel can reduce annual GHG emissions from SGE by 76% provided combined cycle power plants are  
31 adopted for embedded power generation. The magnitude of these benefits would depend on material inputs, seed  
32 yield as well as the environmental status of the reference fuel. Minimal use of fertilizers, chemicals and  
33 resources and fossil fuel substitution with renewable options can minimize adverse environmental burdens.

34 **Keywords:** *Jatropha curcas*, independent power generation, gas turbines, diesel engines, environmental impact  
35 assessment

36

## 37 1. INTRODUCTION

38 As part of the MINT (Mexico, Indonesia, Nigeria and Turkey) countries, Nigeria is expected to emerge as one of the  
39 world's economic giants by 2050, as a result of the rapid population growth and economic activities [1]. This  
40 projection can position Nigeria to be the third most populous country in the world [2], with the country's economy  
41 comparable to France, Germany and the United Kingdom. The projected economic growth, however, cannot be  
42 achieved under Nigeria's current energy realities.

43 There is a large imbalance between energy demand and supply in Nigeria. Out of the 14 GW nominal installed  
44 capacity of power-generating plants in 2014, the highest peak electricity ever recorded was 4.5 GW [3]. This leaves  
45 the country's electricity supply rate at below 40% of the installed nominal capacity while energy demand is  
46 projected at about 40 GW in 2015 [3]. This energy deficiency has reduced energy access throughout the country.  
47 Nearly 75% of the rural population is estimated to have no access to grid electricity. The rural population is forced  
48 to depend on fuel wood consumption as the primary source of energy [4]. Those with access to grid electricity suffer  
49 from severe power-outages, epileptic power-supplies and persistent black-outs. The residents in the urban  
50 population and industries are compelled to depend on self-generated electricity using diesel and gasoline engines.  
51 Therefore, energy shortage is one of Nigeria's greatest economic bane.

52 Based on recent surveys, 25.7% of Nigerian households have generators [5], while 70.7% businesses own or share a  
53 generator and this contributes to 60% of businesses' electricity consumption in Nigeria. Ogunbiyi [6] showed that an  
54 average household and business possess more than one generator while Tyler [7] reported that 97% of surveyed  
55 businesses owned generators and use them for 67% of their production time. In 2011, Nigeria was estimated to  
56 operate 60 million electric generators [3]—valued at \$0.25 billion USD based on the 2011 statistics of imported  
57 electric generators [8]. Another estimate reported that local businesses, manufacturers and families spend an average  
58 of \$26 billion annually to operate electric generators. These estimates [3,8] place Nigeria as the lead importer and  
59 operator of decentralized electric generators in Africa. Since exhaust emissions from the consumption of fossil fuels  
60 are one of the largest contributor to greenhouse gas (GHG) emissions, the widespread use of decentralized diesel-  
61 and gasoline-powered generators in Nigeria is a threat to environmental balance. More so, the delivery of fossil  
62 fuels, typically from foreign refineries increases the cost and environmental burdens of these fuels. Nigeria has to  
63 demonstrate a strong commitment to mitigating GHG emissions and developing renewable and sustainable energy  
64 options as a signatory to the Paris Agreement on Climate Change (COP 21) in December 2015. There are optimistic  
65 suggestions that commercialization of renewable fuels could be achieved by the use of energy crops [9]: one such  
66 crop is *Jatropha curcas*.

67 *Jatropha curcas* is favored as one of the promising energy crop in Nigeria because it grows locally and does not  
68 compete for areas directly with food. Typical *Jatropha* oil seeds in Nigeria possess oil yield as high as 53% [9-10]  
69 with promising energy benefits. This oil can be converted into more energy accessible forms such as bio-ethanol, -  
70 gas, -kerosene and -diesel, depending on the conversion process employed [11]. Because of the ability of the plant to  
71 adjust to marginal lands, and adverse climatic conditions, the plant is perceived to be of environmental and  
72 economic benefits, including the reduction (and even the reversal) of rural-to-urban migration through employment  
73 creation and skill development that consequently leads to rural development [12]. These are large assumptions in  
74 environmental sustainability, if considerable amount of fossil-fuels and -derived materials are to be consumed  
75 during the production and use of the *Jatropha* biodiesel fuel.

76 There are ongoing efforts to adopt renewable energy sources to alleviate Nigeria's energy and fuel problems. The  
77 Energy Commission of Nigeria and the United Nations Development Programme (UNDP) have developed a  
78 Renewable Energy Master Plan. This master plan is aimed at integrating renewable energy sources in existing  
79 electricity generation and distribution systems. This will be supported by the National Renewable Energy and  
80 Energy Efficiency Policy (NREEEP), a legislative framework designed to increase power generation capacities and  
81 share of renewable energy sources in Nigeria [13-14]. On approval, renewable energy sources would account for at  
82 least 10% of Nigeria's electricity supply in 2025 [13]. To this effect, small-, medium- and large pilot power plant  
83 projects are proposed across the country for embedded power supply for public facilities and large industrial estates  
84 [6]. The African Development Bank (AfDB), among other development partners, is also currently funding  
85 renewable energy generation and efficiency projects through the Sustainable Energy Fund for Africa (SEFA) to  
86 encourage the generation, distribution and commercialization of clean energy in Africa. Hence, environmental life  
87 cycle assessment is required to assess the environmental status of substitute renewable fuels. Life Cycle Assessment  
88 (LCA) is a useful tool for identifying, quantifying and evaluating the burdens associated with a system, process,  
89 product, or technology [15-16]. It is widely applied in biofuels research to assess the energy requirements and  
90 environmental burdens of fuels, oils and co-products [17-20].

91 In literature, there is sparse information on the environmental burdens associated with widespread use of  
92 decentralized diesel and gasoline generators for self-generated electricity in Nigeria. A few studies [21-23] that have  
93 investigated the LCA of power generation options in Nigeria have considered only the use of natural gas, liquefied  
94 natural gas fuels and oils for thermal power plants. Moss and Gleave [24] showed that Nigeria can reduce emissions  
95 by 63% by replacing individually-owned diesel generators with electricity from large scale natural gas power plants.  
96 The study was however limited and not holistic for a standard LCA because it only considered the direct exhaust

97 emissions of carbon in engines and presented natural gas as the only alternative. Nigeria is said to be one of the top  
98 producers of crude with the largest amount of flared gas in the world [25]. Katsouris and Sayne, [26] described how  
99 stolen crude-oil is shipped from Nigeria to foreign refineries for instant processing and sales through complex co-  
100 loading and along multiple routes to reduce the risk of being caught and to avoid payment of levies. Kessom *et al.*  
101 [27] showed that Nigeria crude oils are subject to inefficient processes and gas flaring activities. More so, the supply  
102 chain for refined products from crude in Nigeria is complex: part of the crude that is produced locally is exported for  
103 sales, while others are transported overseas for processing and imported back into the country as refined products.  
104 Due to fuel shortages, pipeline vandalization, and poor maintenance of pipeline networks; fuels are often transported  
105 from depots and import jetties over long distances using petroleum tankers and usually with empty trips. Imported  
106 fuels are transported over long distances using wide ranges of sea transport vessels. Hence, applying studies that  
107 have assumed the U.S. National or European average as the reference diesel fuel, which in many cases, the  
108 assumptions were not clearly written, cannot be appropriate in the Nigerian context. In other words, a comparative  
109 fuel assessment that excludes local conditions such as multiple transportation distances, flared gas and fugitive  
110 emissions for the diesel reference system under local power generation realities in Nigeria can underestimate or  
111 overestimate the environmental benefits of the alternatives.

112 This study therefore presents the environmental burdens associated with the use of petroleum diesel fuel for power  
113 generation from a life cycle perspective, in an attempt to quantify the environmental burdens associated with self-  
114 generated electricity and proposed embedded power plants in Nigeria. It proposes the use of Jatropha biodiesel as a  
115 less carbon intensive option and examines the environmental implications of fuel displacement with Jatropha  
116 biodiesel. This is subsequent to the study by Onabanjo *et al.* [28] that showed that Jatropha-biodiesel is a worthwhile  
117 substitute for petroleum diesel fuel with significant environmental benefits in power generation. The study  
118 contributes to the published literature on LCA of Jatropha biodiesel production and use [29-32] through the  
119 application of an understanding of realities in the Nigerian context.

120

121 **2. METHODOLOGY**

122 The life-cycle impact studies were carried out using standard LCA methodologies, as described in detail elsewhere  
123 [15-16]. These include the steps of (i) goal and scope definition; (ii) inventory analysis; (iii) impact assessment; and  
124 (iv) interpretation. The goal of the LCA was to account for the environmental burdens associated with the use of  
125 petroleum diesel fuel and *Jatropha* biodiesel in power generating plants in Nigeria. To this effect, a system boundary  
126 that covers the production of petroleum diesel-fuel in Nigeria, was defined for the base-case comparative study —  
127 Figure 1. This incorporates the processes involved in the extraction and lifting of crude-oil from Nigerian oil-wells  
128 (onshore/offshore), local refining of crude-oil to diesel fuel, crude-oil swaps and the export of crude-oil for refining.  
129 It also includes onshore extraction of crude-oil from overseas facilities and its transportation to an overseas refinery  
130 and associated transportation processes. Because only limited pertinent information exists for commercial scale  
131 cultivation of *Jatropha curcas* seeds and production of biodiesel in Nigeria, a generic system was described for  
132 *Jatropha* biodiesel. The processes include *Jatropha* plant cultivation and harvesting, oil extraction, oil conversion via  
133 transesterification and associated transportation processes —Figure 2. The functional unit for this study is defined as  
134 1 kg of fuel consumed in the engine per year. The inventory includes inputs, such as materials, electricity and fuels.  
135 The outputs include wastes and emissions. These data were obtained from the public domain, existing scientific  
136 literatures, with emphasis on local conditions and agricultural farming-systems [20,33-35]. In the event, where the  
137 required data were not available, plausible technical assumptions were adopted from literature. Product allocation  
138 was only considered for glycerol in the *Jatropha* biodiesel fuel production system. Allocation of the glycerol co-  
139 product was undertaken based on energy content of the products. The input, output and emissions were allocated  
140 based on a 90:10 ratio for *Jatropha* biodiesel fuel to glycerol.

141 The life-cycle impacts of *Jatropha* biodiesel-fuel and the reference diesel-fuel were analysed using SimaPRO  
142 8.0.3.14 software, a computational tool developed by Product Ecology Consultants [36]. This software incorporates  
143 comprehensive databases, including U.S. Life-Cycle Inventory (US LCI), Agri-food Libraries, Eco-invent Libraries,  
144 European Reference Life-Cycle Database (ELCD) for several processes and systems and allows the development of  
145 customized modules. The software was used to build and analyze the inventories of *Jatropha* biodiesel-fuel and  
146 diesel-fuel production systems with preference given to Agri-food and Eco-invent libraries. In the absence of  
147 *Jatropha* or country-specific data, technologically close substitutes of inputs were chosen for the present analysis  
148 such as the manure application in SimaPRO, which is based on input of manure application in Colombia and  
149 nitrogen fertilizer application in SimaPRO environment, which is based on field visits in India. The life-cycle impact  
150 was assessed using ReCiPe Midpoint methodology with twelve impact categories, and an egalitarian perspective

151 that views emission contributions on a long-time frame, typically 500 years [34]. The GHG emissions from fertilizer  
152 applications were calculated using the IPCC global-warming potential (GWP) frame of 1, 25 and 298 within a 100  
153 years' time-scale for CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O. Additional environmental impacts, such as eutrophication and acidification  
154 potential, were calculated using inorganic elements such as PO<sub>4</sub>, NO<sub>3</sub> and NH<sub>3</sub> and metals including Pb, Cd, Ni, Zn,  
155 Hg, Cu, and Cr, as emissions to soil, water or air. The emissions associated with the use of farm machinery, lorries  
156 and small transport-vehicles were already taken into account in SimaPRO.

## 157 **2.1. System Boundary for the Reference Diesel Fuel**

158 A generic diesel production and use system, is illustrated in Figure 1. This framework has been developed following  
159 the reported yields of fuels from Nigerian refineries in 2012 [37] and public information available on the export of  
160 crude oil and the importation of refined products into Nigeria [38]. This is to simplify the diesel fuel production  
161 system, which is a complex mixture resulting from diverse crude types and sources, product-refinery processes and  
162 means of transportation.

### 163 **Figure 1: Description/System Boundary for the Reference Diesel System**

164 Crude-oil production includes activities such as oil exploration, drilling, extraction, as well as water and/or gas re-  
165 injection. According to the NNPC Annual Statistical Bulletin [37], the amount of crude-oil extracted from Nigerian  
166 oil-wells in 2012 was 8.53 billion barrels (bbl), of which 34.9 million barrels (mbl) were processed locally in four  
167 national refineries. The refined products were then imported to a local regional storage depots and refineries for  
168 distribution [37]. The rest of the crude-oil extracted was exported overseas via pipelines and Very Large Crude  
169 Carriers (VLCC) for processing —55.4 mbl under a swap arrangement and 22.7 mbl for off-shore processing  
170 agreements (OPAs), although the exact locations of the refineries were not disclosed. The present analysis examined  
171 a swap arrangement for a refined product from a US refinery, located in Chicago, and an off-shore processing  
172 agreement from the Société Ivoirienne de Raffinage (SIR) refinery in Cote d'Ivoire. Importation of diesel fuel into  
173 Nigeria was assumed to be from Saudi Arabia, although there are numerous sources of importation, e.g. India,  
174 Venezuela, the Middle East, neighbouring countries in Africa and many parts of the U.S.A. and Europe. This is  
175 based on the estimated fuel demand in Nigeria, valued at 12 million litres per day (MLPD) in 2012 [38]. The  
176 transportation processes include crude transport to local, SIR and Chicago refineries, refined product transport to  
177 their regional storage, and Nigerian local regional storage depots and refineries and finally diesel transport to  
178 consumer. Sea transport is assumed to be covered using a VLCC of about 200,000 deadweight tonnes —Table 1.

### 179 **Table 1: Transportation Distance & Related Parameters**



180 Local refineries in Nigeria produced 2.63 MLPD of diesel fuel [37] with a product yield of 18.2% - a value deduced  
181 from the reported 2012 annual production of 818,678 metric tonnes of diesel fuel. Thus, from a market diesel-fuel  
182 demand of 12 MLPD [38], it can be deduced that 2.6 MLPD of it was produced locally, 4.3 MLPD and 1.5 MLPD  
183 of diesel fuel were obtained by SWAP and OPA arrangements respectively, while 3.5 MLPD of diesel fuel was  
184 imported into Nigeria, assuming that the yield of product was 18.2% for Bonny light crude-oil and 35.4% for Arab-  
185 medium crude-oil. Thus, the present analysis estimates that 3.36 kg of Bonny light crude-oil and 0.36 kg of Arab-  
186 medium crude-oil are extracted from the ground per kg of diesel fuel consumed.

187 All the above-described processes were simulated in SimaPRO by creating an assembly. The on-shore production of  
188 petroleum and gas products in Nigeria describes crude production and includes datasets for oil production, energy  
189 use and emissions. This is linked to the data for the rest of the world (Saudi Arabia in this case). Allocation for co-  
190 products (crude oil and natural gas) was based on heating value. Because, refining covers the flows of materials and  
191 energy from 1 kg crude oil into the products and co-products (petrol, bitumen, diesel, kerosene, naphtha, refinery  
192 gas, secondary sulphur and electricity), the environmental impacts are allocated accordingly. Transportation  
193 includes pipeline transfer (onshore and offshore), freight and lorry transport. Exhaust and non-exhaust emissions  
194 such as tyre, brake and road wear per tkm are already included in the inventory for transportation. Non-CO<sub>2</sub> exhaust  
195 emissions such as NO<sub>x</sub>, SO<sub>x</sub> and CO considered for the different engines and fuels are stated in Table 2.

196 **Table 2: Inputs of non-CO<sub>2</sub> exhaust emissions from different power plants [28,39-40]**

## 197 **2.2. Jatropha biodiesel Production System**

198 A generic Jatropha farming system is described in Figure 2. This assumes that numerous small-scale farms for  
199 growing Jatropha exist in Ogun-State, Nigeria. The *Jatropha curcas* is planted initially but widely on a small to  
200 medium scale under two scenarios: a) small-scale and, b) a large-scale farming system. The small-scale farming  
201 system (SFS) employs manual labour and relies on rain-fed agricultural system while the large-scale farming system  
202 (LFS) utilizes diesel fuel powered farm machineries for irrigation and related activities. Jatropha plantation of 1  
203 hectare (ha) and over a 20-year period is considered.

204 Jatropha seedlings were assumed to be grown in polythene bags on nursery beds using seeds with 80% claimed  
205 survival rates for 60 days. These are watered at 0.2 L plant<sup>-1</sup> day<sup>-1</sup> and transferred to the field with a plant spacing of  
206 3m x 3m. Field preparation activities include stump removal, clearing, ploughing and harrowing and pits  
207 preparation. The plant takes up carbon dioxide from the technosphere and this is equivalent to the carbon content of  
208 the seeds. In small-scale farming, these activities are usually carried out by manual labour using axes, hoes and

209 cutlasses over several days. We estimated that manual labour for field preparation would require 5 men ha<sup>-1</sup> day<sup>-1</sup>.  
210 The energy expended by manual labour was calculated using the average daily food-intake of 2120 kcal (8.9 MJ)  
211 capita<sup>-1</sup> day<sup>-1</sup>, as estimated for a West African adult [41]. Field preparation in large-scale plantations is presumed  
212 would be undertaken by mechanized farming. Eshton *et al.* [20] and Gmunder *et al.* [42-43] report diesel  
213 consumptions of 12-15 litres (L) of diesel fuel ha<sup>-1</sup> for land preparation, whereas Prueksakorn and Gheewala [35]  
214 concluded that the range is 25-40 L of diesel fuel ha<sup>-1</sup>. Adewoyin [44] reported values of 17-32 L of diesel fuel ha<sup>-1</sup>  
215 at ploughing depths of 20-30 cm on a sandy-loam soil. In Nigeria, farm machinery is rarely new, owned and  
216 properly maintained, so farm machineries often have high fuel consumption rates. We assume twin run of a farm  
217 tractor with a diesel-fuel requirement of 45 L ha<sup>-1</sup> run<sup>-1</sup>. Here, the soil is assumed to be ploughed to a depth of at  
218 least 50 cm and has sandy loam characteristics.

## 219 **Figure 2: Description/System Boundary for the Jatropha biodiesel System**

220 Fertilizer application is not a common practice on small-scale farms in Nigeria due to the costs involved and because  
221 effective fertilizers are rarely produced locally. So, we have not included fertilizer application for the small-scale  
222 farming system, asides the use of compost manure of 0.5 kg plant<sup>-1</sup> yr<sup>-1</sup>. In the large scale farming system, we  
223 assume that 122, 47 and 134 kg ha<sup>-1</sup> yr<sup>-1</sup> of Nitrogen (N), Phosphorus (P), Potassium (K) [35,45] are applied twice  
224 per year for the first three years of the plantation, after which the residues from the Jatropha plantation, such as  
225 husks and seedcake are returned to the field. Contrary to popular opinion about the protective insecticidal and  
226 microbicidal properties of Jatropha plant, Terren *et al.* [45] reported pests and diseases to be prevalent in Jatropha  
227 farming. Thus, it is assumed for this investigation that Jatropha plants do not appear to be protected by their in-built  
228 insecticidal and microbicidal properties. Artificial insecticide applications of 0.04 g plant<sup>-1</sup> of Chloropyrifos 20EC  
229 (organophosphorous-compound, 20%) is assumed to be applied every 3 years, based on local availability, together  
230 with herbicides, Glyphosphate (3 L ha<sup>-1</sup>) and Paraquat (2 L ha<sup>-1</sup>) [35].

231 Weeding, pruning and fertilizing are assumed to be accomplished manually at 5 men ha<sup>-1</sup> day<sup>-1</sup> for the small-scale  
232 farming system while the large scale farming system requires a diesel consumption rate of 25 L ha<sup>-1</sup> run<sup>-1</sup>.  
233 Harvesting is done in both systems at an average of 50 kg of dry seeds per worker<sup>-1</sup> day<sup>-1</sup>. Both systems require these  
234 activities twice per year for the first five years [35]. Gasoline consumption of 40 L ha<sup>-1</sup> yr<sup>-1</sup> per persons was  
235 incorporated in order to account for the transportation of workers in and out of the farm. All other forms of manual  
236 labour, such as those relating to the operation of equipment were not included. Irrigation is considered for the large  
237 scale farming, although the average annual precipitation in Ogun-State exceeds 1000 mm. Irrigation is assumed to  
238 be supplemented daily by 8 L of water per plant per application for the first 5 years and during the dry season that

239 lasts up to six months, i.e. between October and March. Also, this activity involves the use of farm machinery with  
240 diesel fuel requirement of 60 L ha<sup>-1</sup>. The small- and large-scale farming systems require additional 60 L ha<sup>-1</sup>yr<sup>-1</sup> for  
241 miscellaneous activities such as lighting and security respectively.

242 Typically, a seed yield range of 3 to 14 tonnes of dry seed ha<sup>-1</sup> yr<sup>-1</sup> is reported [19,33] for good soil and as low as 0.7  
243 tonnes ha<sup>-1</sup> yr<sup>-1</sup> for poor soil or wasteland [47]. Studies by Achten *et al.* [48] showed that a minimum yield  
244 requirement of 2 tonnes ha<sup>-1</sup> yr<sup>-1</sup> is required for a sustainable Jatropha farming system. Hence, this study has adopted  
245 a standard seed yield of 2.5 tonnes ha<sup>-1</sup> yr<sup>-1</sup> for both farming systems. Although, this is a pessimistic yield-value  
246 assumption in view of the current rapid advancements in Jatropha farming, spoilage is nevertheless likely during and  
247 after harvesting due to poor use of storage facilities in Nigeria. Adverse ambient conditions such as high  
248 temperatures and humidity are also contributing factors. Other losses, such as product theft could be suffered by  
249 farmers: this would result in such an overall low-seed recovery. The study assumes a centralized fruit-cracking and  
250 expelling hub facility for multiple Jatropha farms. Farms are typically located near villages which are farther away  
251 from cities in Nigeria, transportation distances of up to 50 km from the plantation field was included, alongside with  
252 an additional 40 km for transportation to the biodiesel-production facility. The crop is assumed to be transported by  
253 a farm truck of 20 tonnes capacity with fuel consumption rate of 20 miles per gallon (14.1 litres per 100 km).

254 Available power at the required time is a severely limiting factor in Nigeria. Thus, small-scale industrial facilities  
255 will likely choose the least expensive and readily available technology for expelling oil. Seeds are assumed to be  
256 sun-dried and harnessed by manual labour. The technology assumed, in this study, for extracting oil from the dry  
257 seed is cold pressing considering a standard conversion facility that is available to all farming systems. This process  
258 begins with the use of a fruit cracking machine to remove the seed shells, followed by an oil expeller that ejects oil  
259 from the seeds: finally, a filtering unit is used to purify the oil. Oil yield of 35% was assumed and the residue (i.e.  
260 the seed cake) is returned to the field to supplement the applied organic fertilizer. It is deduced that 2.5 tonnes of dry  
261 Jatropha seed will yield approximately 0.88 tonnes of crude seed-oil, 0.66 tonnes of seed cake and 1.05 tonnes of  
262 seed husk, with oil yields of 35% and husk yield of 42% respectively. To reduce the fraction of free fatty acids the  
263 oil is first pre-treated by allowing it to react with methanol and sulphuric acid [20], followed by a base-catalyzed  
264 transesterification reaction in an 80 L biodiesel batch-reactor, which has 97% efficiency. The mixture of glycerol  
265 and biodiesel fuel produced is separated in the presence of excess water. All the above described inputs are  
266 summarized in Table 3. Land use is considered using the default SimaPRO parameters. Here, Jatropha is considered  
267 a permanent crop and assumed to occupy former arable lands, bare lands, and primary and secondary lands. The

268 total value of the land transformed is estimated using the average productivity  $\text{ha}^{-1} \text{ year}^{-1}$  and the lifetime of the  
 269 plantation.

### 270 **Table 3: Inventory for Jatropha biodiesel System**

#### 271 **2.3. Life cycle Assessment**

272 This study assumed the use of 5 kVA and 30 kVA diesel generators with power factor of 0.8 for self-generated  
 273 electricity in Nigeria. Embedded power plant (industrial diesel and gas turbines) were considered in the place of  
 274 self-generated electricity and these include: a) 200 kVA diesel generator, b) 126 MW open cycle gas turbine  
 275 (OCGT) and c) 375 MW combined cycle gas turbine (CCGT) power plants. Jatropha biodiesel was considered as  
 276 the renewable substitute to the reference diesel fuel. The environmental impact categories for the different engine  
 277 cases were calculated from their respective life cycle emissions per kg of fuel and based on the engine's average fuel  
 278 consumption rate. For appropriate comparison, results are expressed per MWh of electricity generated annually.

## 279 **3. RESULTS**

### 280 **3.1. Life Cycle Environmental Impact**

281 The environmental burdens associated with the use of the reference diesel fuel in the above-listed engines are  
 282 summarised in Figures, 3a-k and sub-sections 3.1.1-3.1.6. Results are also presented for the Jatropha biodiesel fuel  
 283 cases (SFS and LFS) for comparison. Unless stated otherwise, the LFS is mainly used for comparison, since this is  
 284 the high-input system and the worst-case scenario.

285 **Figure 3a-k: Environmental Contributions as a Function of fuel types, farming systems and engine**  
 286 **application: a) Climate Change, b) Ozone Depletion, c) Freshwater Eutrophication, d) Marine**  
 287 **Eutrophication, e) Fossil Depletion, f) Metal Depletion, g) Ionizing Radiation, h) Photochemical Oxidant**  
 288 **Formation, i) Particulate Matter Formation, j) Eco-toxicity and k) Terrestrial Acidification.**

289 SFS – small-scale farming system; LFS – large-scale farming system; SGE – self-generated electricity; EPG – embedded power generation

#### 290 **3.1.1. Climate Change and Ozone Depletion**

291 Climate Change (CC) uses  $\text{CO}_2$  equivalents (eq.) to account for major GHG emissions such as  $\text{CO}_2$ , methane,  
 292 nitrogen oxide and fluorinated gases that result from human activities and are responsible for increasing global  
 293 temperatures. Ozone Depletion (OD) on the other hand quantifies substances that erode the ozone layer in the  
 294 stratosphere using trichlorofluoromethane (CFC-11) as the reference [49]. The results in Figure 3a show that the use  
 295 of the reference diesel fuel in 5 kVA and 30 kVA diesel generators can contribute 1625 and 833  $\text{kg CO}_2 \text{ eq./MWh}$  to

296 CC respectively. For industrial engines, the environmental contributions from diesel fuel consumption are 643 kg  
297 CO<sub>2</sub> eq./MWh (for 200 kVa diesel engine), 698 kg CO<sub>2</sub> eq./MWh (for OCGT) and 459 kg CO<sub>2</sub> eq./MWh (for  
298 CCGT). The GHG emission for industrial engines are at least lower than 57% of emissions from to the diesel-  
299 operated 5 kVA engines. In terms of OD (Figure 3b), the annual environmental contributions from SGE are 2.04 g  
300 CFC-11 eq./MWh (for 5 kVA engines) and 1.04 g CFC-11 eq./MWh (for 30 kVA engines). These values can reduce  
301 to 0.81 g CFC-11 eq./MWh (for 200 kVA diesel engine), 0.88 g CFC-11 eq./MWh (for OCGT) and 0.58 g CFC-11  
302 eq./MWh (for CCGT) by switching to embedded power generation. Additional benefits can be achieved by  
303 integrating Jatropha biodiesel in these engines. Jatropha biodiesel fuel substitution in 5 kVA engines can prevent  
304 352 kg CO<sub>2</sub> eq./MWh (CC) and 1.91 g CFC-11 eq./MWh (OD) corresponding to 22% and 94% reduction  
305 respectively. Integrating Jatropha biodiesel in other engines used in this study can result in reductions ranging from  
306 973 - 1227 kg CO<sub>2</sub> eq./MWh for CC and about 2 g CFC-11 eq./MWh for OD. The best-case scenario is the Jatropha  
307 biodiesel powered CCGT and the reductions nearly offset the impact of SGE in 5 kVA engines. For further  
308 reductions, a small-scale farming approach can be adopted. This ensures an additional 15% and 1% in CC and OD  
309 contributions respectively from the LFS cases.

### 310 **3.1.2. Freshwater and Marine Eutrophication**

311 Eutrophication considers the accumulation of nutrients in the environment and how they affect water quality and the  
312 ecosystem [49]. These include direct and indirect effects of the use of fertilisers and chemical substances and  
313 emissions of ammonia, nitrates, nitrogen oxides and phosphorous on the ecosystem, a process differentiated into  
314 freshwater eutrophication (FE) —Figure 3c and marine eutrophication (ME) —Figure 3d. The use of the reference  
315 diesel fuel in 5 kVA diesel generators can contribute 4.71 g P eq./MWh and 0.39 kg N eq./MWh to FE and ME  
316 respectively. These values are minimal with 30 kVA diesel generators —2.41 g P eq./MWh, (FE) and 0.20 kg N  
317 eq./MWh (ME) and at most 1.33 g P eq./MWh (FE), and 0.11 kg N eq./MWh (ME) for the CCGT case. Fuel  
318 substitution with Jatropha biodiesel increases FE and ME, as annual contributions of 283.64 g P eq./MWh (FE), and  
319 3.01 kg N eq./MWh (ME) are obtained for the 5 kVA engines and 145.32 g P eq./MWh (FE), and 1.54 kg N  
320 eq./MWh (ME) for the 30 kVA engines. In embedded power plants, the use of the Jatropha biofuel contributes  
321 between 88.70 g P eq./MWh (CCGT) and 134.96 g P eq./MWh (OCGT) to FE. The contributions to ME, on the  
322 other hand, are 0.94 kg N eq./MWh (CCGT) and 1.4 g N eq./MWh (OCGT) based on the use of embedded power  
323 plants. These contributions to FE and ME from the Jatropha LFS can be reduced significantly by 83% and 96%  
324 across all engine types, if small-scale farming systems are adopted. While the impact on marine eutrophication can

325 be reduced below the final values of the reference diesel fuel cases, fresh water eutrophication are 10-11 times more  
326 than those of the LFS.

### 327 **3.1.3. Fossil and Metal Depletion**

328 Fossil depletion (FD) quantifies the rate of consumption of fossil fuels and minerals while metal depletion accounts  
329 for the unsustainable consumption of metals. The results in Figure 3e show that a decline of 3521 kg oil eq./MWh  
330 (for 5 kVA engines) and 1804 kg oil eq./MWh (for 30 kVA engines) can result from SGE. The annual contributions  
331 to FD from embedded power generation is 1392 kg oil eq./MWh (for 200 kVA diesel engines), 1512 kg oil  
332 eq./MWh (for OCGT) and 994 kg oil eq./MWh (for CCGT). The use of Jatropha biodiesel in these engines however  
333 can minimize fossil depletion by avoiding the use of 2907 and 1489 kg oil eq./MWh in 5 kVA and 30 kVA diesel  
334 generators respectively. The highest potentials are observed with the embedded power plants. Here, FD was reduced  
335 to 243 kg oil eq./MWh (for 200 kVA diesel engines), 292 kg oil eq./MWh (for OCGT) and 192 kg oil eq./MWh (for  
336 CCGT), a 81-83% reduction from when diesel only was used. The small-scale farming system can ensure an  
337 additional 5% reduction in FD from the LFS.

338 Metal depletion as much as 13.02 kg Fe eq./MWh (for 5 kVA) and 6.67 kg Fe eq./MWh (for 30 kVA) were  
339 observed from Jatropha biodiesel-operated generators (Figure 3f). These values reduced to 4.07 kg Fe eq./MWh in  
340 the CCGT but still as much as 6.19 kg Fe eq./MWh for OCGT. All MD values from the Jatropha biodiesel fuel cases  
341 are significantly higher than the environmental contributions from diesel powered engines, even in self-generation  
342 scenarios.

### 343 **3.1.4. Ionizing Radiation and Photochemical Oxidant Formation**

344 Ionizing radiation, quantified as kBq uranium-235 (U235) eq. takes into account radiations such as  $\alpha$ -,  $\beta$ - and  $\gamma$ -rays  
345 resulting from human activities and their toxicological effects on human health. The impact of SGE in this category  
346 include 167 kBq U235 eq./MWh and 85 kBq U235 eq./MWh for 5 and 30 kVA diesel generators respectively  
347 (Figure 3g). The embedded power generators reduced the impact values to 66 kBq U235 eq./MWh (for 200 kVA  
348 diesel engines), 72 kBq U235 eq./MWh (for OCGT) and 47 kBq U235 eq./MWh (for CCGT), but still twice as  
349 much as the case of Jatropha biodiesel in self-generating engines. The renewable embedded power options are  
350 beneficial in terms of ionizing radiation effects as they ensure an overall reduction of about 88% from 5 kVA diesel  
351 engines.

352 Photochemical Oxidant Formation (POF) reflects contributions to ground level ozone formation and accumulation.  
353 Ozone is formed from increased interaction between volatile organic compounds and nitrogen oxides in the presence

354 of heat and radiations from sunlight [49]. At high concentration, ozone has toxic effects on human, and promotes the  
355 formation of smog that reduces visibility although it is highly useful in the stratosphere to prevent global warming.  
356 POF accounts for exhaust emissions such as sulphur dioxide, nitrogen oxides, and non-methane volatile (NMVOC)  
357 that are released during engine operation. Thus, the contributions (Figure 3h) from small diesel powered generators  
358 include 22.81 kg NMVOC (5 kVA) and 11.69 kg NMVOC (30 kVA). Diesel-operated embedded power plant  
359 however contribute 9.02 kg NMVOC (200 kVA large diesel), 9.80 kg NMVOC (OCGT) and 6.44 kg NMVOC  
360 (CCGT) respectively to POF. A fuel substitution with Jatropha biodiesel for SGE can therefore ensure a reduction of  
361 about 84%, values of 3.63 and 1.86 kg NMVOC for 5 kVA and 30 kVA diesel engines respectively. With embedded  
362 power generation options, the values reduce further to 1.44, 1.73 and 1.14 kg NMVOC for 200 kVA diesel, OCGT  
363 and CCGT engines respectively.

### 364 **3.1.5. Particulate Matter Formation**

365 Particulate matter formation (PMF) accounts for particles as small as 10  $\mu\text{m}$ , which are generated from human and  
366 industrial activities and can trigger a number of respiratory health problems such as asthma, allergies etc. In this  
367 study, the contributions to PMF are largely from Jatropha biodiesel LFS. Here, the use of the fuel for self-generated  
368 electricity contributes 4.64 kg  $\text{PM}_{10}$  eq./MWh (5 kVA) and 2.38 kg  $\text{PM}_{10}$  eq./MWh (30 kVA) —See Figure 3i.  
369 These values are 30% higher than the reference diesel fuel cases and could have resulted from plant cultivation as  
370 well as those resulting from fertilizer application. The contributions from the renewable embedded power generation  
371 options are much lower with values of 1.83 kg  $\text{PM}_{10}$  eq./MWh, 2.21 kg  $\text{PM}_{10}$  eq./MWh and 1.45 kg  $\text{PM}_{10}$  eq./MWh  
372 from 200 kVA large diesel, OCGT and CCGT engines respectively, a 35-58% reduction in environmental  
373 contributions when compared to the Jatropha biodiesel fuel cases. The contributions from the LFS can be reduced by  
374 adopting a small-scale farming approach to Jatropha production. This can ensure an additional reduction of 56% in  
375 PMF as compared to the LFS, an overall reduction of 34-40% in PMF across all engine types in the reference diesel  
376 fuel cases.

### 377 **3.1.6. Ecotoxicity and Terrestrial Acidification**

378 Ecotoxicity (ET) accounts for emission of substances that are above the tolerance levels of toxicity and can include  
379 human, fresh water, marine, and terrestrial toxicity. This study shows that the use of Jatropha biodiesel has adverse  
380 contributions on ecotoxicity, with a range of 8223-16050 kg 1,4-DB eq./MWh depending on engine capacity —  
381 Figure 3j. This range is about 21-54% higher than those of the reference diesel fuel in 5 kVA and 30 kVA diesel  
382 generators and is as a result of direct application of chemicals, and fertilizers related substances. It also includes the



383 contributions from the use of chemicals for oil conversion processes. The use of the *Jatropha* biodiesel in embedded  
384 power plants can reduce ET to 6346 kg 1,4-DB eq./MWh (200 kVA), 7637 kg 1,4-DB eq./MWh (OCGT) and 5019  
385 kg 1,4-DB eq./MWh (CCGT) annually; however, these values are still twice as much as the reference diesel fuel  
386 cases.

387 In the case of Terrestrial Acidification (TA) as shown in Figure 3k, the contributions include a range between 9.54  
388 and 4.89 kg SO<sub>2</sub> eq./MWh from the consumption of diesel in 5 kVA and 30 kVA diesel generators, values that  
389 reduced up to 2.69 kg SO<sub>2</sub> eq./MWh with CCGT operation. The contributions from *Jatropha* biodiesel fuel  
390 consumption were much higher and similar to diesel fuel consumption in self-generation capacities even under best  
391 case scenarios with CCGT. The contributions include 28.69 and 4.89 kg SO<sub>2</sub> eq./MWh from *Jatropha* biodiesel fuel  
392 substitution in 5 kVA and 30 kVA diesel generators, as well as 11.34 kg SO<sub>2</sub> eq./MWh, 13.65 kg SO<sub>2</sub> eq./MWh and  
393 8.97 kg SO<sub>2</sub> eq./MWh in 200 kVA diesel, OCGT and CCGT engines respectively. Acid deposition is largely  
394 contributed by the emission of acid gases (NO<sub>x</sub> and SO<sub>2</sub>) as well as inputs from fossil energy sources in *Jatropha*  
395 farming and oil conversion processes. Therefore, a small input system can be adopted and this ensures a 20-34%  
396 reduction in terrestrial acidification for direct fuel substitution in the different engine cases.

### 397 **3.2. Sensitivity Analysis**

398 The environmental benefits highlighted in this study are based on a number of model scenarios and point estimates  
399 with underlying uncertainties that can make the results more sensitive to one or more parameters. Sensitivity  
400 analysis was conducted on varying seed yield levels and based on the increasing use of fossil fuels, fertilizer and  
401 chemicals to ascertain their effects on the different environment impact categories. The outcomes are presented in  
402 Figure 4a-d. Figure 4a show the radar chart of the sensitivity analysis conducted based on seed yields of 3.5 and 7  
403 tonnes ha<sup>-1</sup> yr<sup>-1</sup>. The sensitivity analysis therefore shows that an increased seed yield of 3.5 tonnes ha<sup>-1</sup> yr<sup>-1</sup> can  
404 reduce the environmental burdens by 16-29% while a seed yield of 7 tonnes ha<sup>-1</sup> yr<sup>-1</sup> can ensure a reduction of 40-  
405 63% across the different environmental impact categories. The impact categories, CC and POF, were the most  
406 sensitive to seed yield while the rest had similar environmental performance as the base-case scenario. A  
407 conservative seed yield of 2.5 tonnes ha<sup>-1</sup> yr<sup>-1</sup> was adopted in this study; however, a range of 0.4-12 tonnes ha<sup>-1</sup> yr<sup>-1</sup>  
408 is reported in literature [48] that differs with agricultural inputs as well as climatic and abiotic conditions [50].  
409 Lower seed yield beyond 2.5 tonnes ha<sup>-1</sup> yr<sup>-1</sup> was however not considered due to the minimum seed yield  
410 recommendations of 1-2 tonnes ha<sup>-1</sup> yr<sup>-1</sup> for sustainable farming of *Jatropha curcas* [48,51], yields that are typical  
411 for farming activities on waste and degraded lands.



412 For sensitivity analysis based on a 50% increased use of fossil fuels and electricity, as shown in Figure 4b, there was  
413 a 0-10% increase in the different environmental impact categories. The increased use of fossil fuels accounts mainly  
414 for diesel fuel consumption in farm equipment and machineries while electricity covers the energy generation from  
415 fossil fuel sources. For diesel fuel consumption, POF had the highest variation with nearly 10% increase while CC,  
416 ME and IR had ~6% variation, and TA and FD had ~4% variation. OD and MD had the least variations with values  
417 less than 2%. Similar experiments for electricity use show an increase of 10% in the environmental burdens for CC  
418 while the environmental impact categories, POF, PMF, TA and FD increased by ~8%. The rest were less than 4%.  
419 Figure 4c show the sensitivity analysis conducted based on a 50% reduction in the use of fertilizer and chemicals. A  
420 50% increase in use of fertilizer and chemicals brought about ~20% increase in the environmental contributions to  
421 OD, TA, FD, POF, PMF, MD and CC. The most sensitive impact categories for increased fertilizer application  
422 include FE (45%), ME (45%) and ET (23%) while IR (45%) for increased chemical use including the consumption  
423 of methanol and sulphuric acid. The sensitivity analysis on transportation, as shown in Figure 4d show that a 50%  
424 increase in the distance covered for the transportation of seeds, oil and biodiesel fuel can bring about a 14%  
425 deviation in POF and 8% for ME and PMF. Other environmental mechanisms such as CC, TA and FD have  
426 deviations of ~6%.

427 **Figure 4a-d: Radar chart of the sensitivity analysis: a) seed yield, b) fossil fuel use and electricity, c) fertilizer**  
428 **application and chemical use and d) transportation of Jatropha seeds, oil and biodiesel fuel.**

#### 429 4. DISCUSSION

430 Nigeria is considered as one of the least contributor to GHG emissions globally with annual CO<sub>2</sub> emissions of 0.54  
431 tonnes CO<sub>2</sub>-eq. per capita [52-53], according to the 2011 World Development Indicators. This ranked the country as  
432 the 159<sup>th</sup> emitter of CO<sub>2</sub> based on emissions per capita, but 39<sup>th</sup> emitter of CO<sub>2</sub> out of 196 countries based on total  
433 CO<sub>2</sub> produced —88 megatonnes in 2011. The country-level rankings were based on the total CO<sub>2</sub> emissions from  
434 burning of primary solid, liquid and gaseous fossil fuels including emissions from gas flaring and cement  
435 production, but there are no indications that it included emissions from self-generated electricity. To account for  
436 SGE, this study estimates a value of 389 million tonnes CO<sub>2</sub> eq. on total CO<sub>2</sub> produced, which corresponds to 2.07  
437 tonnes CO<sub>2</sub>-eq. per capita at 2011 estimated population [53]. Thus, in addition to the country-level rankings, Nigeria  
438 positions as 112 emitters of CO<sub>2</sub> among the global CO<sub>2</sub> emissions per capita index, and 16<sup>th</sup> position based on total  
439 CO<sub>2</sub> produced. By 2050, Nigeria's population is expected to exceed 400 million [2] and the country can be operating  
440 up to a projected 150 million electric generators, if the current practice of SGE persists. This can cause annual GHG  
441 emissions of 847 million tonnes CO<sub>2</sub> eq. that places the country potentially as one of the top ten emitters of CO<sub>2</sub>.

442 The LCA results obtained in this study are therefore useful for estimating the annual emission contributions from all  
443 the midpoint ReCiPE impact categories selected. They are also important for comparing the alternative power  
444 generation options.

445 The above estimation for annual GHG emission have assumed that 68% of privately-owned 60 million electric  
446 generators in Nigeria are diesel operated for 7 hours per day and have engine capacity of 5 kVA capacity or less  
447 with power factor of 0.8 [3-8, 54]. Engine availability was assumed to be low as 50% due to poor maintenance  
448 culture that increases the downtime of engines and the report on the operating hours of generators per household  
449 [54]. While these assumptions provide an estimate, parameters such as engine performance and efficiency varies  
450 with time and ambient conditions. Others such as engine capacity, duration of run, fuel choice etc. depends on user  
451 behavior as well as socio-economic factors. For policy development and implementation, a detailed LCA informed  
452 by real data or accompanied by a thorough survey would be required. This is because of the uncertainties associated  
453 with generic data. For Nigeria and similar developing countries, there is often limited environmental information on  
454 the contributions, nature and consequences of direct and indirect emissions, as such attention should be directed to  
455 obtaining robust data.

456 We have considered climate change as the most relevant local environmental indicator, although all the  
457 environmental impact categories are equally important. This is based on the country's recent commitment to  
458 mitigate greenhouse gas emissions on the Paris Treaty on Climate Change. We propose that addressing the country's  
459 shortfalls in electricity supply should not only be the priority, environmental sustainability amongst other factors  
460 should be at the forefront. As a party to the United Nations Framework Convention on Climate Change (UNFCCC)  
461 and Kyoto Protocol, Nigeria can demonstrate a strong commitment to sustainable development by providing  
462 renewable alternatives to private-operated small generating sets. Measureable goals can be achieved by quantifying  
463 the environmental impact of current energy capacities with comparative assessment of sustainable alternatives, as  
464 presented in the study for Jatropha biodiesel fuel substitution. This can then be supported with targets and  
465 monitoring to ensure environmental protection.

466 This study has explored the egalitarian perspective, a choice that assumes the longest time-frame for emission  
467 impact in the various environmental mechanisms, as opposed to the short-time frame for the individualist  
468 perspective or the dependence on a commonly accepted guidelines for the hierarchist perspective. All the LCA  
469 results obtained are thereby worst-case scenarios and exerts prevention as the mitigation strategy or precautionary  
470 principle. We have selected the midpoint ReCiPE methodology for characterisation due to the low uncertainties  
471 associated with this approach, even in the absence of regional data. Unlike the endpoint approach, this method

472 provides direct and individual environmental contributions without further damage level assessments. With  
473 additional and well-structured regional information on the fate and exposure of chemical compounds in the  
474 environment, further damage level assessments can be conducted with the mid-point indicators to achieve three end-  
475 point indicators (damage to ecosystems, human health and resource availability). The disadvantage of the midpoint  
476 approach; however, is that the results are less accessible and difficult to interpret by non-technical audience but the  
477 end-point estimations are best suited for well-developed and understood systems and results can be accompanied  
478 with large uncertainties.

479 The study also showed that emission reductions can be achieved with the use of more energy efficient plants with or  
480 without fuel substitution. The deployment of heavy duty engines for embedded power generation without fuel  
481 substitution can ensure reductions of 56-72% in all the environmental impact categories. By substituting the diesel  
482 fuel with as a less carbon intensive option, *Jatropha* biodiesel, overall reductions can vary from 27% to 98% in the  
483 impact categories: CC, OD, POF, PMF, ET, IR and FD, depending on the farming methods. Similar results are  
484 presented in [31, 35, 55-56] where previous studies show that the life cycle production of *Jatropha* biodiesel have a  
485 positive environmental balance, and magnitude of benefits depends on system inputs and product allocation. Ndong  
486 et al. [57] showed that the use of *Jatropha* biodiesel in West Africa reduced GHG emissions by 72% while Achten et  
487 al. [19] presented these GHG reductions as  $55 \pm 16\%$  to the reference system. There are however negative  
488 environmental contributions such as terrestrial acidification, fresh and marine eutrophication and metal depletion  
489 that results from the use of *Jatropha* biodiesel and the contributions exceeds the diesel reference system.

490 These negative contributions in the *Jatropha* biodiesel system are resulting from the production and application of  
491 synthetic fertilizers, and emissions associated with the use chemicals and fossil fuels in farm equipment and  
492 industrial plants. Analysis of the *Jatropha* biodiesel LFS shows that *Jatropha* farming is the main cause of emissions  
493 in the seven categories including eutrophication, particulate matter formation and terrestrial acidification while oil  
494 conversion processes contributed mainly to metal depletion, fossil depletion, photochemical oxidant formation and  
495 ecotoxicity. Studies by [19-20,58] attribute the use of nitrogen and phosphate fertilizers and the consumption of  
496 fossil derived fuels for the agricultural farming of *Jatropha curcas* has the main contributions to environmental  
497 burdens. These fertilizers tend to leak into nearby rivers and streams, and can be released accidentally into the air  
498 during application, depending on the soil's properties and environmental conditions. Eshton et al. [20] showed a net  
499 GHG contribution of  $848 \text{ kg t}^{-1}$  from the farming and end-use of *Jatropha* biodiesel in Tanzania and these were  
500 mainly from fertilizer application. From the above studies, *Jatropha* biodiesel is established as a low-burden and not  
501 a burden-free system, due to the inputs of nitrogen and phosphorus fertilizers, and fossil fuels. The use of chemicals

502 such as methanol and sulphuric acid also contributes. Thus, to minimize the negative contributions associated with  
503 large-scale system, small-scale farming system can be adopted. While the life cycle impact towards TA, ME and  
504 PMF can be minimized beyond those of the reference diesel fuel cases in the SFS, the impact towards FE, MD and  
505 ET cannot be minimized. Overall, the magnitude of benefits of the *Jatropha* biofuel system will largely depend on  
506 material inputs, seed yield as well as the environmental status of the reference fuel. Previous studies [59-61] that  
507 have examined the LCA of the European standard fuel report GHG emissions in the range of 4.9-24 g CO<sub>2</sub>-eq./MJ  
508 (well-to-tank analysis), corresponding to 0.34-1.02 kg CO<sub>2</sub>-eq./kg. This is less than a third of the value obtained in  
509 this study, as such the *Jatropha* biodiesel system does not have a favorable outcome with a European standard fuel.

510 For drastic reduction measures as shown in the sensitivity analysis results for fertiliser application and seed yield,  
511 minimal use of fertilizers and chemicals will be important. Seed and oil yield can be improved with the use of  
512 superior genetic seed strains, agricultural practices and soil conditions [19,48]. Rathbauer et al. [62] showed that  
513 harvesting and storage conditions are key aspects for oil quality. *Jatropha* was originally recommended to be grown  
514 on degraded or wastelands with minimal agricultural inputs [63] due to the crop's resilient abilities to adapt to poor  
515 soil and adverse climatic conditions. However, studies by Achten et al. [20], Ariza-Montobbio et al. [64] and  
516 Axelsson et al. [65] showed that there are significant costs on seed and oil yield. For energy and environmental  
517 balance, a seed yield of at least 1-2 tonnes per hectare (ha) per year is recommended [48, 51]. Other key measures to  
518 limit negative environmental contributions include minimised use or part-replacement of fossil fuel sources for  
519 powering farm equipment, and industrial machines for oil conversion. Wang et al. [51] and Brittain, and Lualadio,  
520 [66] showed that there could be a significant reduction in the life cycle impact of *Jatropha* biodiesel by co-product  
521 allocation; however, this depends on a number of factors including seed yield, energy and material inputs that are  
522 often site-specific. Site-specific LCA informed by practical farming can therefore better inform minimization  
523 strategies. The study has considered human energy expenditure in the *Jatropha* farming system [67], since farming  
524 in Africa is heavily dependent on manual processes. However, the results show that human energy input is relatively  
525 small to the overall system and has no added influence on the environment impact. In this regard, a socio-economic  
526 LCA can provide the impact of human energy input, particularly relating to quality of life and costs associated and  
527 especially for the small-scale farming system.

528 This study did not associate increased seed yield with increased use of irrigation, fertilizer etc, although seed yield  
529 can be linked to improved farming method and inputs. This is because *Jatropha* farming is yet to be practiced  
530 commercially in Nigeria and there is known to what extent that fertilizer use will improve *Jatropha* seed production.  
531 It is also of worth to mention that the scope of the study did not cover social and economic assessment of *Jatropha*

532 biodiesel production. Land use changes and carbon stock associated with commercial production of the fuel as well  
533 as infrastructure development were not considered due to limited local information. The study has only taken into  
534 account the main non-CO<sub>2</sub> exhaust emissions (NO<sub>x</sub>, SO<sub>x</sub> and CO) which excludes short-lived climate pollutants  
535 (SLCPs) such as black carbon (BC), hydrofluorocarbons, volatile organic compounds (VOCs) that are shown in  
536 recent times to negatively affect climate change and associated with a number of human respiratory and  
537 cardiovascular problems. These SLCPs have a short lifespan of a few days to weeks and varies widely with local  
538 conditions. For instance, BC are formed from incomplete combustion of fuels including diesel and biodiesel fuels  
539 and from open burning of agricultural waste and wood in cook stoves. Therefore, the inclusion of SLCPs,  
540 particularly BC can increase the CC impact of the fuels used in the study. Further work can elaborate on the impact  
541 of these compounds. Other aspects that can be investigated which are out of scope of this work is the cost  
542 implication of the use of these fuel in diesel engines. Previous studies by the authors [68] showed that the use of the  
543 fuels in large industrial gas turbines requires a form of financial instrument to ensure economic viability; hence  
544 economic performance analysis will be vital in the light of this environmental assessment. The study has considered  
545 the direct substitution of fuels in engines based on the close characteristics of diesel and biodiesel fuels. Since, these  
546 fuels have a relatively high biodegradability rate [69], there are possibility for increased maintenance of engines.  
547 Such additional environmental impacts and maintenance requirements were not included in the study. For overall  
548 life cycle outlook of the Jatropha biodiesel system, further work will aim at expanding the study with socio-  
549 economic impact assessment.

## 550 5. CONCLUSION

551 This environmental impacts associated with self-generated electricity and proposed embedded power plants in  
552 Nigeria were assessed based on a life cycle perspective. The use of privately-owned diesel powered generators of  
553 5kVA or less can result in annual life cycle GHG emissions of 389 million tonnes CO<sub>2</sub> eq., a value corresponding to  
554 2.07 tonnes CO<sub>2</sub>-eq. per capita. This can position the country as the 112 emitters of CO<sub>2</sub> among the global emissions  
555 per capita index, and 16<sup>th</sup> position based on total CO<sub>2</sub> produced. By 2050, the country could be one of the ten  
556 emitters of CO<sub>2</sub> if current self-generation activities persist. To satisfy Nigeria's energy demand, there should be a  
557 diversification in the energy mix for power generation and a reduction in GHG emissions concurrently. This can be  
558 achieved with embedded power plants with Jatropha biodiesel, as the alternative fuel. By substituting the diesel fuel  
559 with Jatropha biodiesel, 352 kg CO<sub>2</sub> eq./MWh can be avoided, a 22% reduction. Further reductions in CC of up to  
560 76% can be achieved with embedded power generation. Such projects can significantly reduce the environmental  
561 impact of self-generated electricity across most impact categories, however at a cost on terrestrial acidification,

562 metal depletion, freshwater- and marine-eutrophication. These contributions are resulting from the production and  
563 application of synthetic fertilizers, and emissions associated with the use chemicals and fossil fuels in farm  
564 equipment and industrial plants. An adoption of a small-scale farming approach, the reduction of fertilizer and  
565 chemicals at the cost of yield and the replacement of fossil fuels with renewable options can further reduce the  
566 contributions from the Jatropha biodiesel system.

567

ACCEPTED MANUSCRIPT

## 568 REFERENCES

- 569 [1] Lunn, J. and Harari, D., 2014. Nigeria 2015: analysis of election issues and future prospects. *Economic*  
570 *Indicators*, 2, p.14.
- 571 [2] United Nations Department of Economic and Social Affairs (UN DESA). 2007. *Small-Scale Production and*  
572 *Use of Liquid Biofuels in Sub-Saharan Africa: Perspectives for Sustainable Development*, Prepared by  
573 Energy and Transport Branch, Division for Sustainable Development (PAPER NO. 2: DESA/DSD/2007/2)
- 574 [3] The Nigerian Energy Support Programme (NESP). 2014. *The Nigerian Energy Sector -an Overview with a*  
575 *Special Emphasis on Renewable Energy, Energy Efficiency and Rural Electrification*, 1-168,  
576 <<https://www.giz.de/en/downloads/giz2014-en-nigerian-energy-sector.pdf>> (last accessed on 24/2/2015).
- 577 [4] International Energy Agency (IEA). 2014. *World Energy Outlook 2014*. IEA Publications, Paris.
- 578 [5] National Bureau of Statistics (NBS). 2011. *Annual Abstract of Statistics of the Federal Republic of Nigeria*  
579 <http://www.nigerianstat.gov.ng/pages/NBS%20eLibrary>. Last accessed on 06/9/2015
- 580 [6] Ogunbiyi, D. 2013. Lagos State Government Energy Initiatives Electricity Board (LSEB). Presented at  
581 Exco/PS Retreat.
- 582 [7] Tyler, Gerald. 2002. *Public and private electricity provision as a barrier to manufacturing competitiveness.*  
583 *Africa Region findings*; no. 221. Washington, DC: World Bank.  
584 [http://documents.worldbank.org/curated/en/2002/12/2082423/nigeria-public-private-electricity-provision-](http://documents.worldbank.org/curated/en/2002/12/2082423/nigeria-public-private-electricity-provision-barrier-manufacturing-competitiveness-public-private-electricity-provision-barrier-manufacturing-competitiveness)  
585 [barrier-manufacturing-competitiveness-public-private-electricity-provision-barrier-manufacturing-](http://documents.worldbank.org/curated/en/2002/12/2082423/nigeria-public-private-electricity-provision-barrier-manufacturing-competitiveness-public-private-electricity-provision-barrier-manufacturing-competitiveness)  
586 [competitiveness](http://documents.worldbank.org/curated/en/2002/12/2082423/nigeria-public-private-electricity-provision-barrier-manufacturing-competitiveness-public-private-electricity-provision-barrier-manufacturing-competitiveness)
- 587 [8] UN COMTRADE, 2015. United Nations commodity trade statistics database. URL: <http://comtrade.un.org>. Last accessed on 06/9/2015
- 588
- 589 [9] Aransiola, E. F., Daramola, M. O. Ojumu, T. V., Aremu, M. O., Layokun, S. K. Bamidele, O. S. 2012.  
590 *Nigerian Jatropha curcas Oil Seeds: Prospect for Biodiesel Production in Nigeria, International Journal of*  
591 *Renewable Energy Research*, 2(2): 317-325.
- 592 [10] Umaru, M. and Aberuagba F. 2012. Characteristics of Typical Nigerian *Jatropha curcas* oil Seeds for  
593 Biodiesel Production, *Research Journal of Chemical Sciences*, 2(10): 7-12.
- 594 [11] Jingura, R., Matengaifa, R., Musadamba, D., Musiyiwa, K. 2011. Characterisation of land types and agro-  
595 ecological conditions for production of *Jatropha* as a feedstock for biofuels in Zimbabwe, *Biomass and*  
596 *Bioenergy*, 35: 2080–6.
- 597 [12] Demirbas, A. 2008. The importance of bioethanol and biodiesel from biomass, *Energy Sources Part B:*  
598 *Economics, Planning, and Policy* 3(2):177–185



- 599 [13] Energy Commission of Nigeria (ECN). 2012. Draft National Energy Master Plan.  
600 <[http://www.energy.gov.ng/index.php?option=com\\_docman&task=doc\\_download&gid=102&Itemid=49](http://www.energy.gov.ng/index.php?option=com_docman&task=doc_download&gid=102&Itemid=49)>  
601 (last accessed on 06/9/2014).
- 602 [14] Nigerian National Petroleum Corporation, (NNPC). 2007. Biofuels Development in Nigeria, International  
603 Renewable Energy Conference, Abuja, March 16-19.
- 604 [15] ISO (International Organization for Standardization). 2006a. Environmental Management – Life Cycle  
605 Assessment – Principles and Framework, International Organization for Standardization, Geneva,  
606 Switzerland, Report No.: ISO 14040
- 607 [16] ISO (International Organization for Standardization). 2006b. Environmental management. Life cycle  
608 assessment Requirements and guidelines, International Organization for Standardization, Geneva,  
609 Switzerland, Report No.: ISO 14044.
- 610 [17] Renó, M.L.G., Lora, E.E.S., Palacio, J.C.E., Venturini, O.J., Buchgeister, J. and Almazan, O., 2011. A  
611 LCA (life cycle assessment) of the methanol production from sugarcane bagasse. *Energy*, 36(6), pp.3716-  
612 3726.
- 613 [18] Gnansounou, E., Dauriat, A., Villegas, J. and Panichelli, L., 2009. Life cycle assessment of biofuels:  
614 energy and greenhouse gas balances. *Bioresource technology*, 100(21), pp.4919-4930.
- 615 [19] Achten, W. M., Almeida, J., Fobelets, V., Bolle, E., Mathijs, E., Singh, V. P. *et al.* 2010. Life cycle  
616 assessment of Jatropha biodiesel as transportation fuel in rural India, *Applied Energy*, 87(12), 3652-3660.
- 617 [20] Eshton, B., Katima, J. H. Y., Kituyi, E. 2013. Greenhouse gas emissions and energy balances of Jatropha  
618 biodiesel as an alternative fuel in Tanzania, *Biomass and Bioenergy*, 58:95-103.
- 619 [21] Safaei, A., Freire, F. and Henggeler Antunes, C., 2015. Life-Cycle Greenhouse Gas Assessment of  
620 Nigerian Liquefied Natural Gas Addressing Uncertainty. *Environmental science & technology*, 49(6),  
621 pp.3949-3957.
- 622 [22] Gujba, H., Mulugetta, Y. and Azapagic, A., 2010. Environmental and economic appraisal of power  
623 generation capacity expansion plan in Nigeria. *Energy policy*, 38(10), pp.5636-5652.
- 624 [23] Gujba, H., Mulugetta, Y. and Azapagic, A., 2011. Power generation scenarios for Nigeria: An  
625 environmental and cost assessment. *Energy Policy*, 39(2), pp.968-980.
- 626 [24] Moss, T. and Gleave, M. 2014. How Can Nigeria Cut CO2 Emissions by 63%? Build More Power Plants.  
627 Centre for Global Development. [http://www.cgdev.org/blog/how-can-nigeria-cut-co2-emissions-63-build-](http://www.cgdev.org/blog/how-can-nigeria-cut-co2-emissions-63-build-more-power-plants)  
628 [more-power-plants](http://www.cgdev.org/blog/how-can-nigeria-cut-co2-emissions-63-build-more-power-plants) (last accessed on 06/9/2015).



- 629 [25] EIA (Energy Information Administration), 2015. Independent statistics and analysis  
630 <[https://www.eia.gov/beta/international/analysis\\_includes/countries\\_long/Nigeria/nigeria.pdf](https://www.eia.gov/beta/international/analysis_includes/countries_long/Nigeria/nigeria.pdf)> (last  
631 accessed on 06/9/2015).
- 632 [26] Katsouris, C. and Sayne, A. 2013. Nigeria's Criminal Crude: International Options to Combat the Export of  
633 Stolen Oil, The Royal Institute of International Affairs, 1-85
- 634 [27] Kessom, W., Unnasch, S., Moretta, J. 2009. Life Cycle Assessment Comparison of North American and  
635 Imported Crudes. Alberta Energy Research Institute, File No: AERI 1747, pp:1-220
- 636 [28] Onabanjo, T. and Di Lorenzo, G., 2015, June. Energy Efficiency and Environmental Life Cycle  
637 Assessment of Jatropha for Energy in Nigeria: A "Well-to-Wheel" Perspective. In *ASME 2015 9th*  
638 *International Conference on Energy Sustainability collocated with the ASME 2015 Power Conference, the*  
639 *ASME 2015 13th International Conference on Fuel Cell Science, Engineering and Technology, and the*  
640 *ASME 2015 Nuclear Forum* (pp. V001T06A004-V001T06A004). American Society of Mechanical  
641 Engineers.
- 642 [29] Pandey, K. K., Pragma, N., Sahoo P. K. 2011. Life cycle assessment of small-scale high-input Jatropha  
643 biodiesel production in India. *Applied Energy*, 88(12): 4831–4839
- 644 [30] Liang, S., Xu, M., & Zhang, T. 2013. Life cycle assessment of biodiesel production in China. *Bioresource*  
645 *Technology* 129: 72-77.
- 646 [31] Kaewcharoensombata, U., Prommettab, K., Srinophakun T. 2011. Life cycle assessment of biodiesel  
647 production from Jatropha, *Journal of the Taiwan Institute of Chemical Engineers*, 42(3), 454-462.
- 648 [32] Hagman, J., Nerentorp, M., Arvidsson, R., & Molander, S. 2013. Do biofuels require more water than do  
649 fossil fuels? Life cycle-based assessment of jatropha oil production in rural Mozambique, *Journal of*  
650 *Cleaner Production*, 53, 176-185.
- 651 [33] Whitaker, M., Garvin, H. 2009. Life Cycle Assessment of the Use of Jatropha biodiesel in Indian  
652 Locomotives, Technical Report, NREL/TP-6A2-44428.
- 653 [34] Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J. and Van Zelm, R., 2009. ReCiPe  
654 2008. A life cycle impact assessment method which comprises harmonised category indicators at the  
655 midpoint and the endpoint level, 1.
- 656 [35] Prueksakorn, K., Gheewala, S. H. 2008. Full chain energy analysis of biodiesel from *Jatropha curcas* L. in  
657 Thailand", *Environ Science Technology*, 42:3388–3393.
- 658 [36] Product Ecology Consultants (PRé). 2011. SimaPro Life cycle assessment software", Amersfoort, the  
659 Netherlands.

- 660 [37] Nigerian National Petroleum Corporation, (NNPC). 2012. Annual Statistical Bulletin, Corporate Planning  
661 and Strategy Division, NNPC.
- 662 [38] House of Representative Ad-Hoc Committee (HTADC). 2012. Report of the ad-hoc committee “to verify  
663 and determine the actual subsidy requirements and monitor the implementation of the subsidy regime in  
664 Nigeria”, Resolution no. (HR.1/2012). (Last accessed on 06/9/2014).
- 665 [39] Maina, P., 2014. Investigation of fuel properties and engine analysis of *Jatropha* biodiesel of Kenyan  
666 origin. *Journal of Energy in Southern Africa*, 25(2), pp.107-116.
- 667 [40] Metal, N.F., 2001. Emission Estimation Technique Manual for Non-Ferrous Metal Manufacture Version  
668 1.1.
- 669 [41] van Wesenbeeck, C. F., Keyzer, M. A., Nubé, M. 2009. Estimation of under nutrition and mean calorie  
670 intake in Africa: methodology, findings and implications, 8(37):1-18.
- 671 [42] Gmünder, S., Singh, R., Pfister, S., Adheloya, A., Zah, R. 2012. Environmental Impacts of *Jatropha*  
672 *curcas* Biodiesel in India, *Journal of Biomedicine and Biotechnology*, 1-11.
- 673 [43] Gmünder, S. M., Zah, R., Bhattacharjee, S., Classen, M., Mukherjee, P., Widmer, R. 2009. Life cycle  
674 assessment of village electrification based on straight *Jatropha* oil in Chhattisgarh, India, *Biomass and*  
675 *Bioenergy*, 1-9
- 676 [44] Adewoyin, A.O. and Ajav, E.A., 2013. Fuel consumption of some tractor models for ploughing operations  
677 in the sandy-loam soil of Nigeria at various speeds and ploughing depths. *Agricultural Engineering*  
678 *International: CIGR Journal*, 15(3), 67-74.
- 679 [45] Reinhardt, G., Gartner, S., Rettenmaier, N., Munch, J., von Falkenstein, E. 2007. Screening Life Cycle  
680 Assessment of *Jatropha* biodiesel, Commissioned by Daimler A. G., Stuttgart, Prepared by the Institute for  
681 Energy and Environmental Research Heidelberg GmbH.
- 682 [46] Terren, M., Jacquet de Haveskercke, P., Winandy, S. and Mergeai, G. 2012. Attempted cultivation of  
683 *Jatropha curcas* L. in the Lower Senegal River Valley: story of a failure. *Tropicultura*, 30(4): 204-208.
- 684 [47] Ogunwole, J. O. 2014. Development of Commercially Viable Plantations of *Jatropha curcas* L: Case for  
685 Promotion of Its Agricultural Research. *Advances in Plants and Agriculture Research*, 1(3): 00017
- 686 [48] Achten, W.M., Mathijs, E., Verchot, L., Singh, V.P., Aerts, R. and Muys, B., 2007. *Jatropha* biodiesel  
687 fueling sustainability?. *Biofuels, bioproducts and biorefining*, 1(4), pp.283-291.
- 688 [49] Acero, A.P., Rodríguez, C. and Ciroth, A., 2014. LCIA methods–Impact assessment methods in Life Cycle  
689 Assessment and their impact categories. GreenDelta GmbH, Berlin, Germany, p.23.

- 690 [50] Lam, M.K., Lee, K.T., & Mohamed, A.R. 2009. Life cycle assessment for the production of biodiesel: a  
691 case study in Malaysia for palm oil versus *Jatropha* oil. *Biofuels, Bioproducts and Biorefining* 3(6): 601-  
692 612
- 693 [51] Wang, Z., Calderon, M., Lu Y. 2011. Lifecycle assessment of the economic, environmental and energy  
694 performance of *Jatropha curcas* L. biodiesel in China, *Biomass and Bioenergy*, 35: 2893–2902
- 695 [52] World Bank Group (WBG). 2016a. Population, Total <<http://data.worldbank.org/indicator/SP.POP.TOTL>>,  
696 (last accessed on 24/2/2016).
- 697 [53] World Bank Group (WBG). 2016b. CO<sub>2</sub> emissions (metric tons per capita),  
698 <<http://data.worldbank.org/indicator/EN.ATM.CO2E.PC>>, (last accessed on 24/2/2015).
- 699 [54] Oseni, M.O., 2016. Get rid of it: To what extent might improved reliability reduce self-generation in  
700 Nigeria?. *Energy Policy*, 93, pp.246-254.
- 701 [55] Almeida J, Achten W.M.J, Duarte, M.P., Mendes, B, Muys, B. 2011. Benchmarking the environmental  
702 performance of the *Jatropha* biodiesel system through a generic life cycle assessment. *Environ Sci. Technol.*  
703 45:5447–5453.
- 704 [56] Hoefnagels, R., Smeets, E., & Faaij, A. 2010. Greenhouse gas footprints of different biofuel production  
705 systems. *Renewable and Sustainable Energy Reviews* 14(7):1661-1694
- 706 [57] Ndong, R., Montrejaud-Vignoles, M., Saint Girons, O., Gabrielle, B., Pirot, R., Domergue, M.,  
707 Sablayrolles, C. 2009. Life cycle assessment of biofuels from *Jatropha curcas* in West Africa: a field  
708 study. *Global Change Biology Bioenergy*, 1:197–210.
- 709 [58] Prueksakorn, K., Gheewala, S. H., Malakul, P. and Bonnet, S. 2010. Energy analysis of *Jatropha* plantation  
710 systems for biodiesel production in Thailand, *Energy for Sustainable Development*, 14:1–5.
- 711 [59] López, J., Gómez, A., Aparicio, F., Sánchez, J. (2009) Comparison of GHG emissions from diesel,  
712 biodiesel and natural gas refuse trucks of the City of Madrid, *Applied Energy*, 86, 610–615.
- 713 [60] Ahlvik, P., Eriksson, L. (2011) Well to tank assessment – diesel fuel MK1 and EN 590, Report 127057,  
714 rev. 2, Ecotraffic.
- 715 [61] Perimenis, A., Majer, S., Zech, K., Holland, M., Müller-Langer, F. (2010) Lifecycle Assessment of  
716 Transportation Fuels, Deliverable D5 (WP 4 report), German Biomass Research Centre, Leipzig, Germany
- 717 [62] Rathbauer, J., Sonnleitner, A., Pirot, R., Zeller, R. and Bacovsky, D., 2012. Characterisation of *Jatropha*  
718 *curcas* seeds and oil from Mali. *Biomass and bioenergy*, 47, pp.201-210.
- 719 [63] Francis, George, Raphael Edinger, and Klaus Becker. "A concept for simultaneous wasteland reclamation,  
720 fuel production, and socio-economic development in degraded areas in India: Need, potential and

- 721 perspectives of Jatropha plantations." In Natural Resources Forum, vol. 29, no. 1, pp. 12-24. Blackwell  
722 Publishing, Ltd., 2005.
- 723 [64] Ariza-Montobbio, P. and Lele, S. 2010. Jatropha plantations for biodiesel in Tamil Nadu, India: Viability,  
724 livelihood trade-offs, and latent conflict. *Ecological Economics*, 70(2), 189-195.
- 725 [65] Axelsson, L., Franzén, M., Ostwald, M., Berndes, G., Lakshmi, G. and Ravindranath, N.H., 2012. Jatropha  
726 cultivation in southern India: assessing farmers' experiences. *Biofuels, Bioproducts and Biorefining*, 6(3),  
727 pp.246-256.
- 728 [66] Brittain, R. L. and Litaladio, N. 2010. Jatropha: A smallholder Bioenergy Crop-The Potential for Pro-Poor  
729 Development, *Integrated Crop Management*, 8:1-114.
- 730 [67] Grimsby, L.K., Aune, J.B. and Johnsen, F.H., 2012. Human energy requirements in Jatropha oil production  
731 for rural electrification in Tanzania. *Energy for Sustainable Development*, 16(3), pp.297-302.
- 732 [68] Onabanjo, T. O.; Di Lorenzo; Kolios, A. 2015. Economic Analysis of a Jatropha Biodiesel-fired Power  
733 Plant in Nigeria. In Proceedings of the 3rd Sustainable Thermal Energy Management International  
734 Conference, 7th – 8th July 2015, Newcastle upon Tyne, UK.
- 735 [69] Onabanjo, T. O.; Di Lorenzo, G.; Goodger, E. M.; Somorin, Y. A model for simulating microbial fuel  
736 degradation in gas turbines. *International Biodeterioration & Biodegradation*. Accepted. Article in press;  
737 doi: 10.1016/j.ibiod.2016.01.005
- 738

**Table 1–Transportation Distance & Related Parameters**

Sea distance (Forcados Terminal to Gulf Port)	km	12434
Forcados Terminal to Port, Abidjan	km	1048
Forcados Terminal to local refinery	km	920
Gulfport to Chicago Refinery	km	1447
Crude Transfer to SIR refinery	km	100
Crude Transfer to Saudi Arabia refinery (Jubail Port, Saudi Arabia to Forcados Terminal)	km	15662
Gulfport to Nigerian Port	km	12434
Abidjan Port to Nigerian Port	km	1048
Local refinery to local depots	km	5000
Chicago Refinery to Gulfport	km	1447
Crude Transfer from SIR refinery to local refinery	km	300
Crude Transfer from Saudi Arabia refinery to local refinery	km	300

**Table 2– Inputs of non-CO<sub>2</sub> exhaust emissions from different power plants [28, 39-40]**

Engine/Fuel Type	Diesel Engine		Gas Turbine	
	Diesel	Jatropha Biodiesel	Diesel	Jatropha Biodiesel
CO	3.69E-03	1.76E-05	7.92E-06	4.40E-06
NO <sub>x</sub>	1.58E-05	7.92E-04	3.52E-04	5.28E-04
SO <sub>x</sub>	2.67E-02	-	2.12E-03	-

**Table 3-Inventory for Jatropha biodiesel System**

<b>SUB-PROCESSES</b>	<b>SMALL-SCALE FARMING</b>	<b>LARGE-SCALE FARMING</b>
<b>PRE-NURSERY</b>		
Seeds for Nursery	0.769 g seed <sup>-1</sup>	0.769 g seed <sup>-1</sup>
Water for Nursery	0.2 L seed <sup>-1</sup> day <sup>-1</sup> /60 days	0.2 L seed <sup>-1</sup> day <sup>-1</sup> /60 days
Polyethylene Bags (Nursery)	2 g bag <sup>-1</sup>	2 g bag <sup>-1</sup>
Human Labour	1 man day <sup>-1</sup> /60 days	1 man day <sup>-1</sup> /60 days
<b>FIELD PREPARATION</b>		
Tractor Use for Land Preparation	5 men ha <sup>-1</sup> day <sup>-1</sup> /5 days	45 L diesel ha <sup>-1</sup> run <sup>-1</sup>
Weeding/Fertilizer Application	5 men ha <sup>-1</sup> day <sup>-1</sup>	12.5 L diesel ha <sup>-1</sup> run <sup>-1</sup>
Harvesting	50 kg dry seed man <sup>-1</sup> day <sup>-1</sup>	50 kg dry seed man <sup>-1</sup> day <sup>-1</sup>
Fertilizer, N	-	121.48 kg ha <sup>-1</sup> yr <sup>-1</sup>
Fertilizer, P <sub>2</sub> O <sub>5</sub>	-	46.49 kg ha <sup>-1</sup> yr <sup>-1</sup>
Fertilizer, K <sub>2</sub> O	-	133.47 kg ha <sup>-1</sup> yr <sup>-1</sup>
Compost	0.5 kg pit <sup>-1</sup> yr <sup>-1</sup>	-
Glyphosphate (Herbicide)	3 L ha <sup>-1</sup> yr <sup>-1</sup>	3 L ha <sup>-1</sup> yr <sup>-1</sup>
Paraquat (Herbicide)	2 L ha <sup>-1</sup> yr <sup>-1</sup>	2 L ha <sup>-1</sup> yr <sup>-1</sup>
Insecticide	0.04 g plant <sup>-1</sup> yr <sup>-1</sup>	0.04 g plant <sup>-1</sup> yr <sup>-1</sup>
Gasoline Use (Extra)	40 L ha <sup>-1</sup> yr <sup>-1</sup>	40 L ha <sup>-1</sup> yr <sup>-1</sup>
Diesel Use (Extra)	60 L ha <sup>-1</sup> yr <sup>-1</sup>	60 L ha <sup>-1</sup> yr <sup>-1</sup>
Transportation (To Crushing Site)	50 km @20mpg	50 km @20mpg
Water for Insecticide Application	100 L	100 L
Diesel for Irrigation	-	60 L ha <sup>-1</sup>
Irrigation	-	8 L plant <sup>-1</sup> week <sup>-1</sup>
Transport for Irrigation	-	43 km @20 mpg
<b>OIL EXTRACTION</b>		
Cracking Machine	2hp@100 kg hr <sup>-1</sup>	2hp@100 kg hr <sup>-1</sup>
Expeller	37.5hp@ 0.75 ton hr <sup>-1</sup>	37.5hp@ 0.75 ton hr <sup>-1</sup>
Filtering Machine	2hp@160L hr <sup>-1</sup>	2hp@160L hr <sup>-1</sup>
Transportation (Crushing Site to Biodiesel Plant)	40 km@ 20 mpg	40 km@ 20 mpg
<b>OIL CONVERSION</b>		
Electricity for Biodiesel Plant Use	80L/batch @4kWh/batch	80L/batch @4kWh/batch
Electricity for Pre-treatment	14kwh/t	14kwh/t
Sulphuric acid	14kg/t	14kg/t
Methanol	110kg/t	110kg/t
KOH	18kg/t	18kg/t
Steam	660kg/t	660kg/t
Transportation (Biodiesel Plant to Local Site)	50 km @20mpg	50 km @20mpg

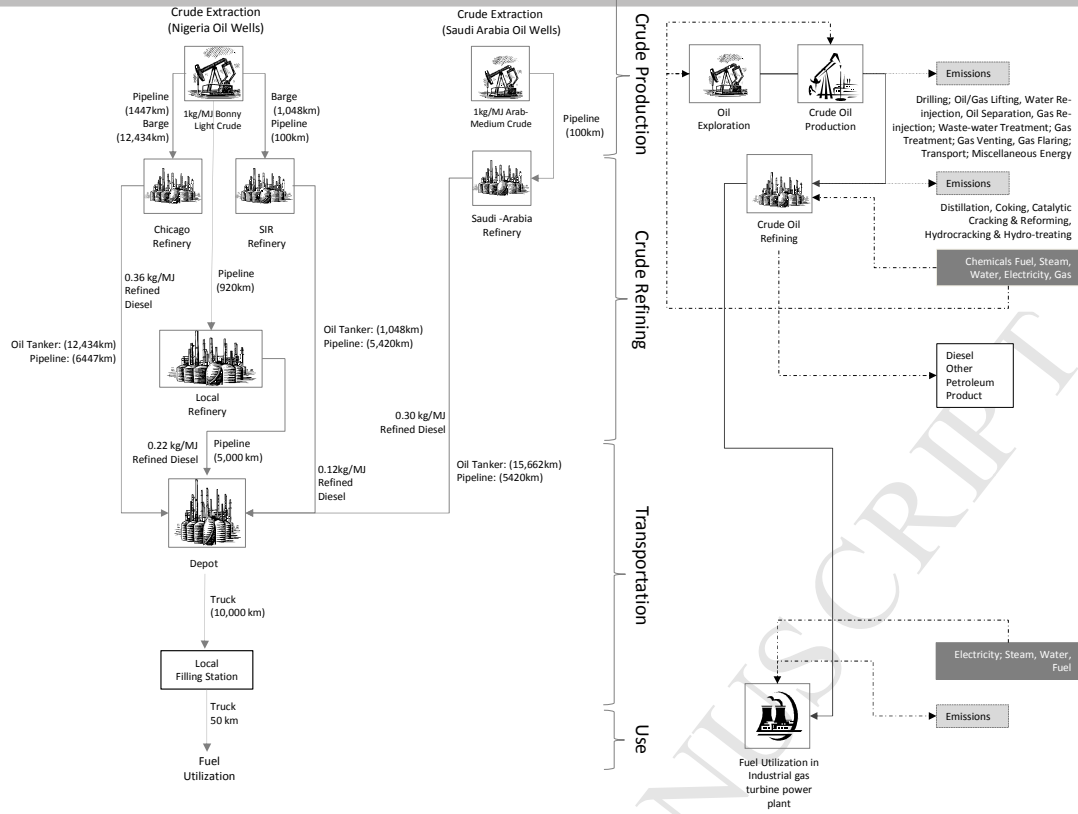


Fig. 1: Description/System Boundary for the Reference Diesel System



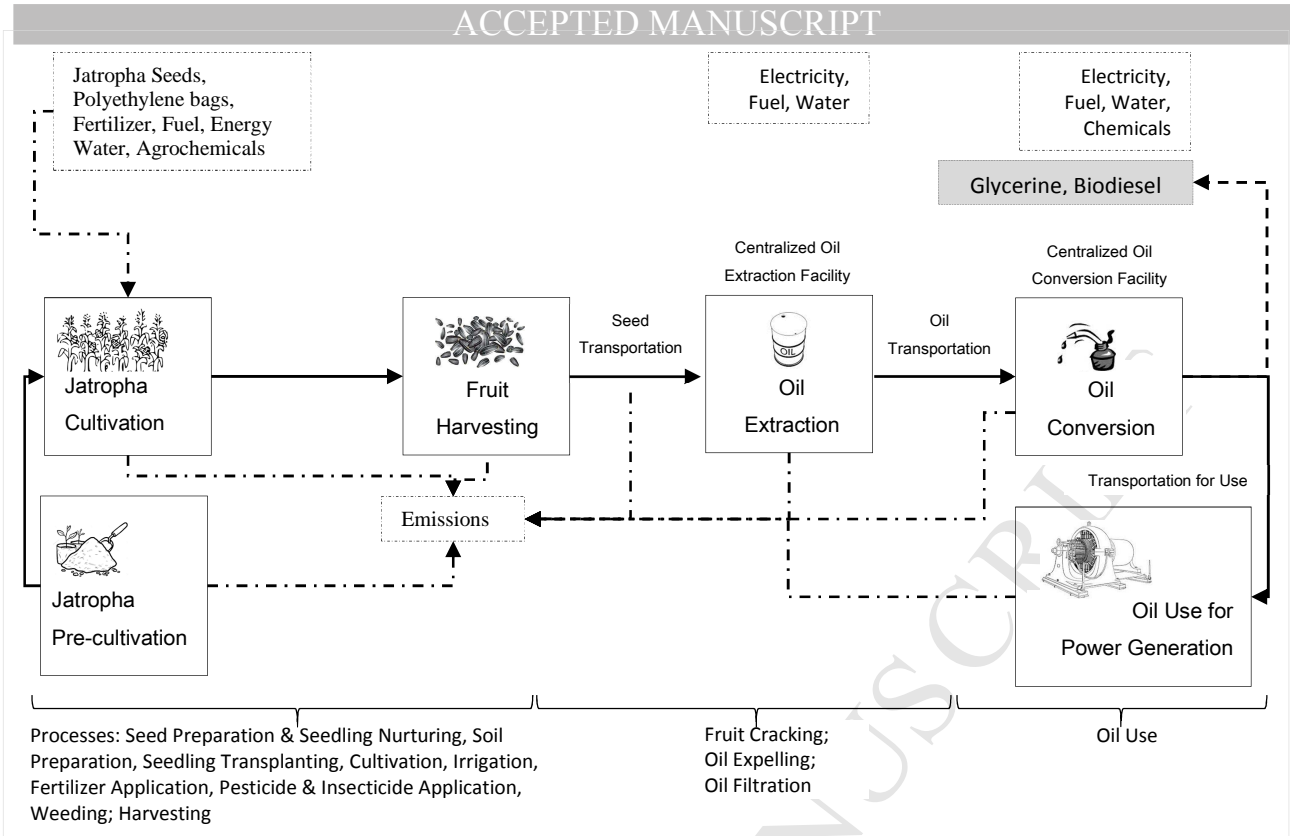
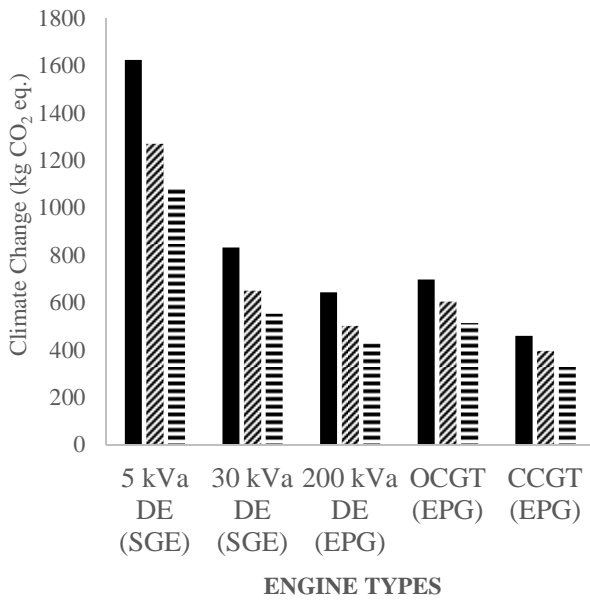
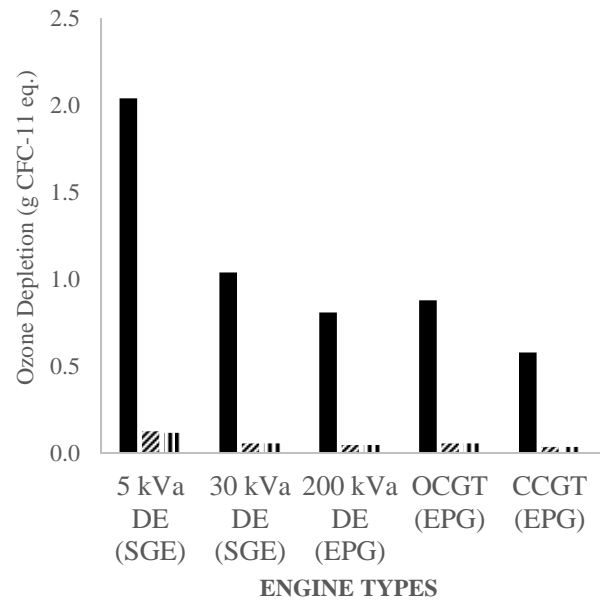


Fig. 2: Description/System Boundary for the Jatropha biodiesel System

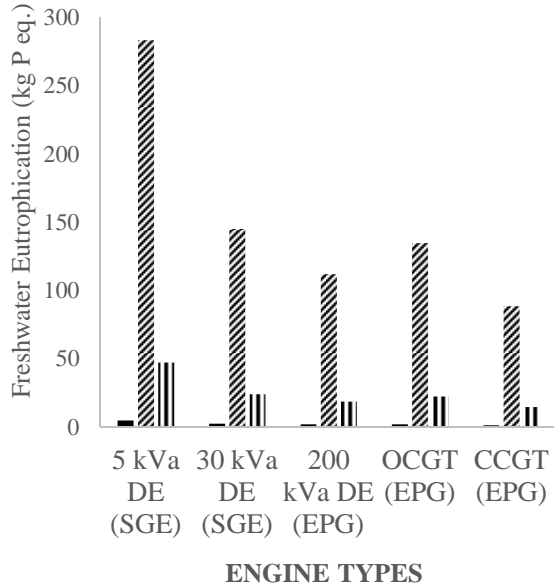
a) Climate Change (CC)



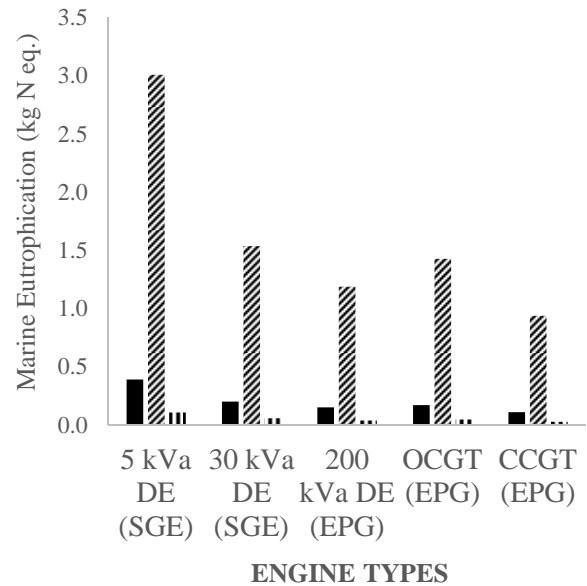
b) Ozone Depletion (OD)



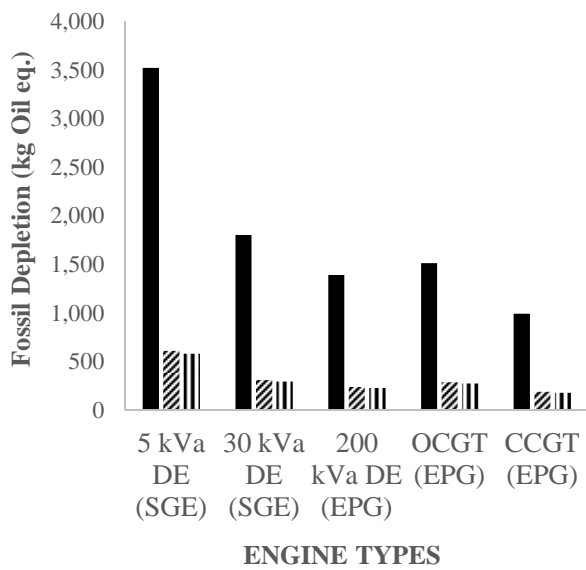
c) Freshwater Eutrophication (FE)



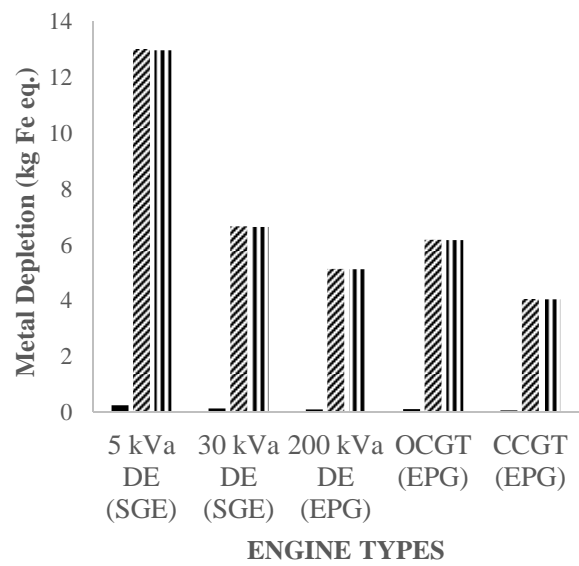
d) Marine Eutrophication (ME)



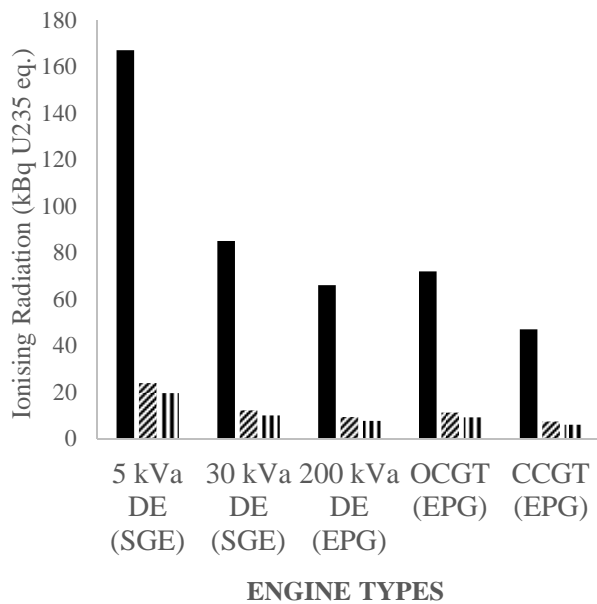
e) Fossil Depletion (FD)



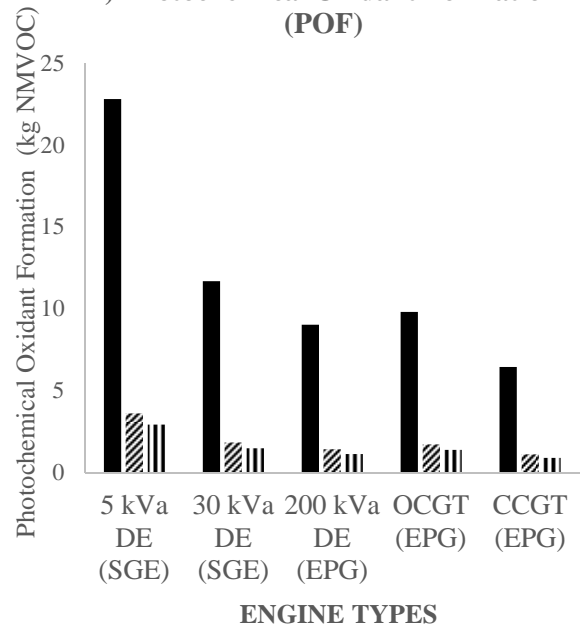
f) Metal Depletion (MD)



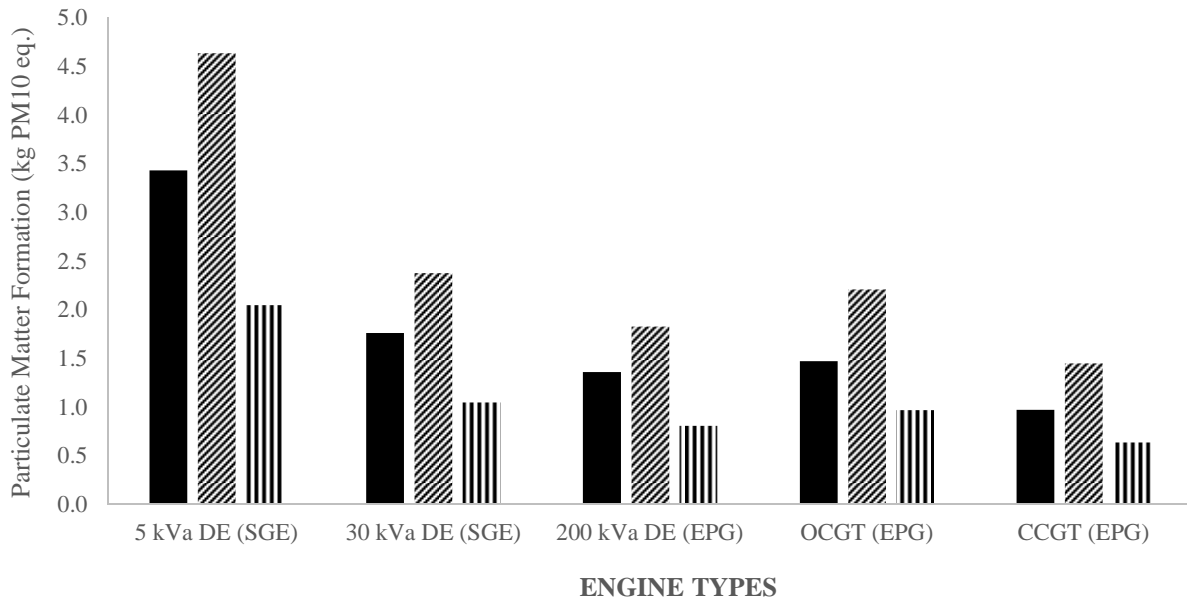
g) Ionising Radiation (IR)



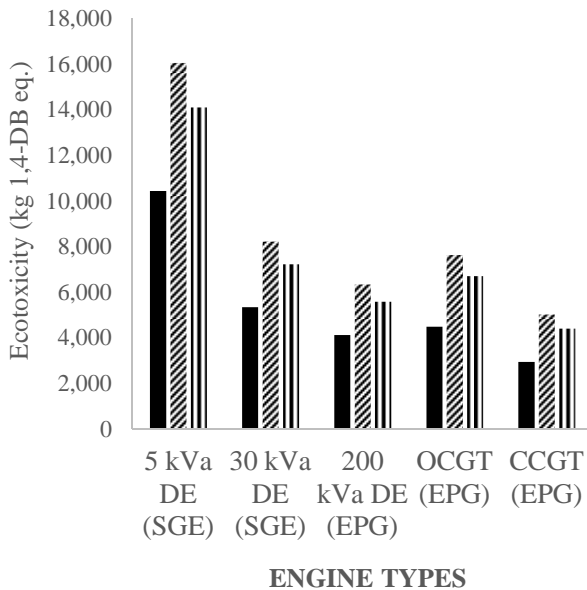
h) Photochemical Oxidant Formation (POF)



## i) Particulate Matter Formation (PMF)



## j) Ecotoxicity (EC)



## k) Terrestrial Acidification (TA)

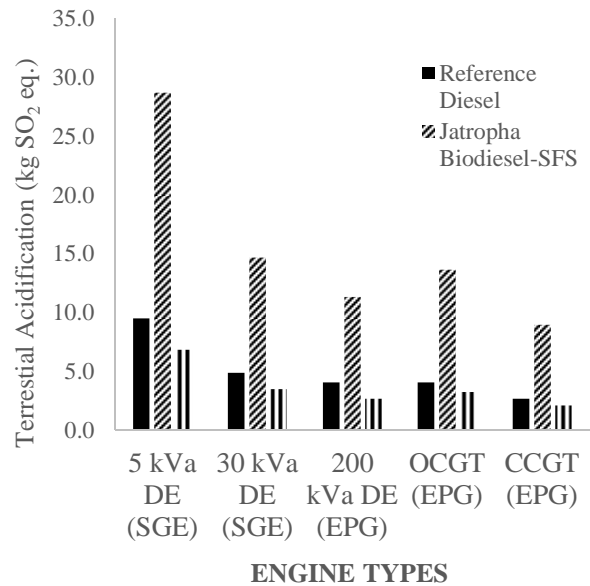
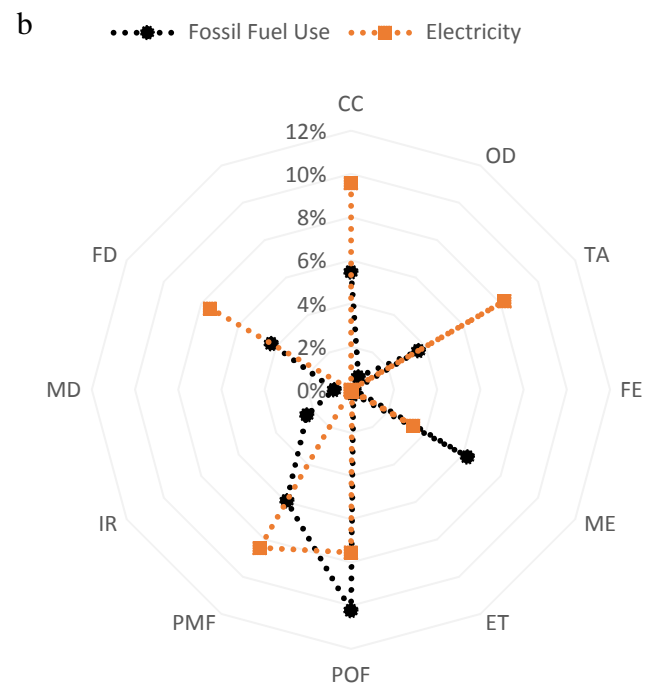


Figure 3a-k: Environmental Contributions as a Function of fuel types, farming systems and engine application: a) Climate Change, b) Ozone Depletion, c) Freshwater Eutrophication, d) Marine Eutrophication, e) Fossil Depletion, f) Metal Depletion, g) Ionising Radiation, h) Photochemical Oxidant Formation, i) Particulate Matter Formation, j) Ecotoxicity and k) Terrestrial Acidification

SFS – small-scale farming system; LFS – large-scale farming system; SGE – self-generated electricity; EPG – embedded power generation

■ Reference Diesel    ▨ Jatropha Biodiesel-SFS    ▤ Jatropha Biodiesel-LFS



ACCEPTED

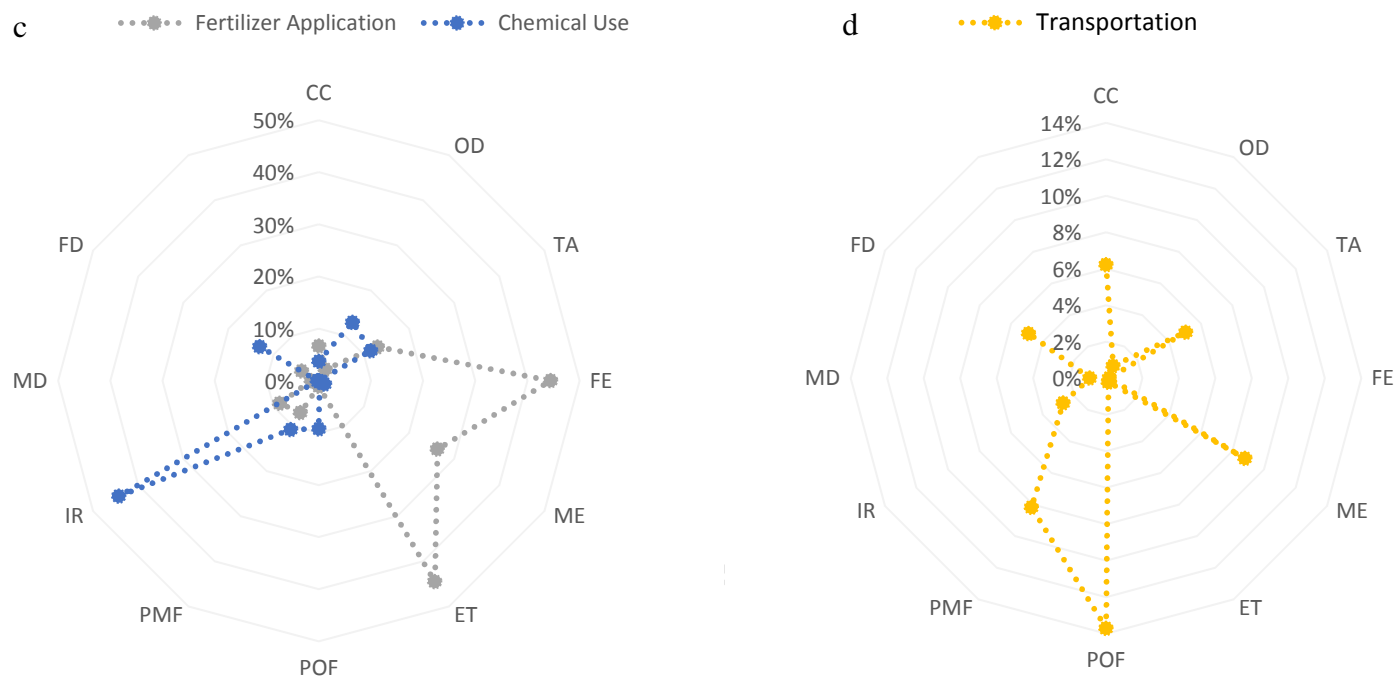


Figure 4a-d: Radar chart of the sensitivity analysis: a) seed yield, b) fossil fuel use and electricity, c) fertilizer application and chemical use and d) transportation of *Jatropha* seeds, oil and biodiesel fuel.

**Highlights**

- Self-generated electricity (SGE) contributes of 1625 kg CO<sub>2</sub> eq./MWh of electricity
- SGE in Nigeria contributes 389 million tonnes CO<sub>2</sub> eq. annually to climate change
- This can rank Nigeria in the top 20 on the global CO<sub>2</sub> emission index
- Jatropha biodiesel in embedded power plants can reduce CO<sub>2</sub> emissions by 22-76%
- Magnitude of benefits depends on plant yield, farming system and engine efficiency