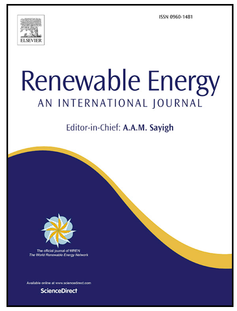

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ABSTRACT

Insufficient available energy has limited the economic growth of Nigeria. The country suffers from frequent power outages, and inconvenient black–outs while residents and industries are forced to depend on self-generated electricity. Life-cycle assessment methodology was used to assess the environmental burdens associated with self-generated electricity (SGE) and proposed embedded power generation in Nigeria. The study shows that SGE from 5 kVA diesel generators contributes to greenhouse gas (GHG) emissions of 1625 kg CO_2 eq./MWh, along with other environmental burdens. Based on a point estimate of diesel electric generators in Nigeria, SGE can contribute 389 million tonnes CO_2 eq. to climate change every year. This can reposition Nigeria as one of the top 20 emitters of CO_2 globally. A mandatory diesel fuel displacement with Jatropha biodiesel can reduce annual GHG emissions from SGE by 76% provided combined cycle power plants are adopted for embedded power generation. The magnitude of these benefits would depend on material inputs, seed yield as well as the environmental status of the reference fuel. Minimal use of fertilizers, chemicals and resources and fossil fuel substitution with renewable options can minimize adverse environmental burdens.

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

1. INTRODUCTION

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

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

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

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

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

In literature, there is sparse information on the environmental burdens associated with widespread use of decentralized diesel and gasoline generators for self-generated electricity in Nigeria. A few studies [21-23] that have investigated the LCA of power generation options in Nigeria have considered only the use of natural gas, liquefied natural gas fuels and oils for thermal power plants. Moss and Gleave [24] showed that Nigeria can reduce emissions by 63% by replacing individually-owned diesel generators with electricity from large scale natural gas power plants. The study was however limited and not holistic for a standard LCA because it only considered the direct exhaust emissions of carbon in engines and presented natural gas as the only alternative. Nigeria is said to be one of the top producers of crude with the largest amount of flared gas in the world [25]. Katsouris and Sayne, [26] described how stolen crude-oil is shipped from Nigeria to foreign refineries for instant processing and sales through complex co-loading and along multiple routes to reduce the risk of being caught and to avoid payment of levies. Kessom *et al.* [27] showed that Nigeria crude oils are subject to inefficient processes and gas flaring activities. More so, the supply chain for refined products from crude in Nigeria is complex: part of the crude that is produced locally is exported for sales, while others are transported overseas for processing and imported back into the country as refined products. Due to fuel shortages, pipeline vandalization, and poor maintenance of pipeline networks; fuels are often transported from depots and import jetties over long distances using petroleum tankers and usually with empty trips. Imported fuels are transported over long distances using wide ranges of sea transport vessels. Hence, applying studies that have assumed the U.S. National or European average as the reference diesel fuel, which in many cases, the assumptions were not clearly written, cannot be appropriate in the Nigerian context. In other words, a comparative fuel assessment that excludes local conditions such as multiple transportation distances, flared gas and fugitive emissions for the diesel reference system under local power generation realities in Nigeria can underestimate or overestimate the environmental benefits of the alternatives.

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

2. METHODOLOGY

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

The life-cycle impacts of Jatropha biodiesel-fuel and the reference diesel-fuel were analysed using SimaPRO 8.0.3.14 software, a computational tool developed by Product Ecology Consultants [36]. This software incorporates comprehensive databases, including U.S. Life-Cycle Inventory (US LCI), Agri-food Libraries, Eco-invent Libraries, European Reference Life-Cycle Database (ELCD) for several processes and systems and allows the development of customized modules. The software was used to build and analyze the inventories of Jatropha biodiesel-fuel and diesel-fuel production systems with preference given to Agri-food and Eco-invent libraries. In the absence of Jatropha or country-specific data, technologically close substitutes of inputs were chosen for the present analysis such as the manure application in SimaPRO, which is based on input of manure application in Colombia and nitrogen fertilizer application in SimaPRO environment, which is based on field visits in India. The life-cycle impact was assessed using ReCiPe Midpoint methodology with twelve impact categories, and an egalitarian perspective that views emission contributions on a long-time frame, typically 500 years [34]. The GHG emissions from fertilizer applications were calculated using the IPCC global-warming potential (GWP) frame of 1, 25 and 298 within a 100 years' time-scale for CO_2, CH_4 and N_2O. Additional environmental impacts, such as eutrophication and acidification potential, were calculated using inorganic elements such as PO_4, NO_3 and NH_3 and metals including Pb, Cd, Ni, Zn, Hg, Cu, and Cr, as emissions to soil, water or air. The emissions associated with the use of farm machinery, lorries and small transport-vehicles were already taken into account in SimaPRO.

2.1. System Boundary for the Reference Diesel Fuel

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

Figure 1: Description/System Boundary for the Reference Diesel System

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

Table 1: Transportation Distance & Related Parameters

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

All the above-described processes were simulated in SimaPRO by creating an assembly. The on-shore production of petroleum and gas products in Nigeria describes crude production and includes datasets for oil production, energy use and emissions. This is linked to the data for the rest of the world (Saudi Arabia in this case). Allocation for co-products (crude oil and natural gas) was based on heating value. Because, refining covers the flows of materials and energy from 1 kg crude oil into the products and co-products (petrol, bitumen, diesel, kerosene, naphtha, refinery gas, secondary sulphur and electricity), the environmental impacts are allocated accordingly. Transportation includes pipeline transfer (onshore and offshore), freight and lorry transport. Exhaust and non-exhaust emissions such as tyre, brake and road wear per tkm are already included in the inventory for transportation. Non-CO_2 exhaust emissions such as NOx, SOx and CO considered for the different engines and fuels are stated in Table 2.

Table 2: Inputs of non-CO_2 exhaust emissions from different power plants [28,39-40]

2.2. Jatropha biodiesel Production System

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

Jatropha seedlings were assumed to be grown in polythene bags on nursery beds using seeds with 80% claimed survival rates for 60 days. These are watered at 0.2 L plant^{-1} day^{-1} and transferred to the field with a plant spacing of 3m x 3m. Field preparation activities include stump removal, clearing, ploughing and harrowing and pits preparation. The plant takes up carbon dioxide from the technosphere and this is equivalent to the carbon content of the seeds. In small-scale farming, these activities are usually carried out by manual labour using axes, hoes and cutlasses over several days. We estimated that manual labour for field preparation would require 5 men ha^{-1} day^{-1}. The energy expended by manual labour was calculated using the average daily food-intake of 2120 kcal (8.9 MJ) $capita^{-1}$ day^{-1}, as estimated for a West African adult [41]. Field preparation in large-scale plantations is presumed would be undertaken by mechanized farming. Eshton *et al.* [20] and Gm¨under *et al.* [42-43] report diesel consumptions of 12-15 litres (L) of diesel fuel ha^{-1} for land preparation, whereas Prueksakorn and Gheewala [35] concluded that the range is 25-40 L of diesel fuel ha^{-1}. Adewoyin [44] reported values of 17-32 L of diesel fuel ha^{-1} at ploughing depths of 20-30 cm on a sandy-loam soil. In Nigeria, farm machinery is rarely new, owned and properly maintained, so farm machineries often have high fuel consumption rates. We assume twin run of a farm tractor with a diesel-fuel requirement of 45 L ha^{-1} run^{-1}. Here, the soil is assumed to be ploughed to a depth of at least 50 cm and has sandy loam characteristics.

Figure 2: Description/System Boundary for the Jatropha biodiesel System

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

Weeding, pruning and fertilizing are assumed to be accomplished manually at 5 men ha^{-1} day^{-1} for the small-scale farming system while the large scale farming system requires a diesel consumption rate of 25 L ha^{-1} run^{-1}. Harvesting is done in both systems at an average of 50 kg of dry seeds per $worker^{-1}$ day^{-1}. Both systems require these activities twice per year for the first five years [35]. Gasoline consumption of 40 L ha^{-1} yr^{-1} per persons was incorporated in order to account for the transportation of workers in and out of the farm. All other forms of manual labour, such as those relating to the operation of equipment were not included. Irrigation is considered for the large scale farming, although the average annual precipitation in Ogun-State exceeds 1000 mm. Irrigation is assumed to be supplemented daily by 8 L of water per plant per application for the first 5 years and during the dry season that lasts up to six months, i.e. between October and March. Also, this activity involves the use of farm machinery with diesel fuel requirement of 60 L ha^{-1}. The small- and large-scale farming systems require additional 60 L $ha^{-1}yr^{-1}$ for miscellaneous activities such as lighting and security respectively.

Typically, a seed yield range of 3 to14 tonnes of dry seed ha^{-1} yr^{-1} is reported [19,33] for good soil and as low as 0.7 tonnes ha^{-1} yr^{-1} for poor soil or wasteland [47]. Studies by Achten *et al.* [48] showed that a minimum yield requirement of 2 tonnes ha^{-1} yr^{-1} is required for a sustainable Jatropha farming system. Hence, this study has adopted a standard seed yield of 2.5 tonnes ha^{-1} yr^{-1} for both farming systems. Although, this is a pessimistic yield-value assumption in view of the current rapid advancements in Jatropha farming, spoilage is nevertheless likely during and after harvesting due to poor use of storage facilities in Nigeria. Adverse ambient conditions such as high temperatures and humidity are also contributing factors. Other losses, such as product theft could be suffered by farmers: this would result in such an overall low-seed recovery. The study assumes a centralized fruit-cracking and expelling hub facility for multiple Jatropha farms. Farms are typically located near villages which are farther away from cities in Nigeria, transportation distances of up to 50 km from the plantation field was included, alongside with an additional 40 km for transportation to the biodiesel-production facility. The crop is assumed to be transported by a farm truck of 20 tonnes capacity with fuel consumption rate of 20 miles per gallon (14.1 litres per 100 km).

Available power at the required time is a severely limiting factor in Nigeria. Thus, small-scale industrial facilities will likely choose the least expensive and readily available technology for expelling oil. Seeds are assumed to be sun-dried and harnessed by manual labour. The technology assumed, in this study, for extracting oil from the dry seed is cold pressing considering a standard conversion facility that is available to all farming systems. This process begins with the use of a fruit cracking machine to remove the seed shells, followed by an oil expeller that ejects oil from the seeds: finally, a filtering unit is used to purify the oil. Oil yield of 35% was assumed and the residue (i.e. the seed cake) is returned to the field to supplement the applied organic fertilizer. It is deduced that 2.5 tonnes of dry Jatropha seed will yield approximately 0.88 tonnes of crude seed-oil, 0.66 tonnes of seed cake and 1.05 tonnes of seed husk, with oil yields of 35% and husk yield of 42% respectively. To reduce the fraction of free fatty acids the oil is first pre-treated by allowing it to react with methanol and sulphuric acid [20], followed by a base-catalyzed transesterification reaction in an 80 L biodiesel batch–reactor, which has 97% efficiency. The mixture of glycerol and biodiesel fuel produced is separated in the presence of excess water. All the above described inputs are summarized in Table 3. Land use is considered using the default SimaPRO parameters. Here, Jatropha is considered a permanent crop and assumed to occupy former arable lands, bare lands, and primary and secondary lands. The total value of the land transformed is estimated using the average productivity ha^{-1} $year^{-1}$ and the lifetime of the plantation.

Table 3: Inventory for Jatropha biodiesel System

2.3. Life cycle Assessment

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

3. RESULTS

3.1. Life Cycle Environmental Impact

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

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) Ionizing Radiation, h) Photochemical Oxidant Formation, i) Particulate Matter Formation, j) Eco-toxicity and k) Terrestrial Acidification.

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

3.1.1. Climate Change and Ozone Depletion

Climate Change (CC) uses CO_2 equivalents (eq.) to account for major GHG emissions such as CO_2, methane, nitrogen oxide and fluorinated gases that result from human activities and are responsible for increasing global temperatures. Ozone Depletion (OD) on the other hand quantifies substances that erode the ozone layer in the stratosphere using trichlorofluoromethane (CFC-11) as the reference [49]. The results in Figure 3a show that the use of the reference diesel fuel in 5 kVA and 30 kVA diesel generators can contribute 1625 and 833 kg CO_2 eq./MWh to

CC respectively. For industrial engines, the environmental contributions from diesel fuel consumption are 643 kg CO_2 eq./MWh (for 200 kVa diesel engine), 698 kg CO_2 eq./MWh (for OCGT) and 459 kg CO_2 eq./MWh (for CCGT). The GHG emission for industrial engines are at least lower than 57% of emissions from to the diesel-operated 5 kVA engines. In terms of OD (Figure 3b), the annual environmental contributions from SGE are 2.04 g CFC-11 eq./MWh (for 5 kVA engines) and 1.04 g CFC-11 eq./MWh (for 30 kVA engines). These values can reduce 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 eq./MWh (for CCGT) by switching to embedded power generation. Additional benefits can be achieved by integrating Jatropha biodiesel in these engines. Jatropha biodiesel fuel substitution in 5 kVA engines can prevent 352 kg CO_2 eq./MWh (CC) and 1.91 g CFC-11 eq./MWh (OD) corresponding to 22% and 94% reduction respectively. Integrating Jatropha biodiesel in other engines used in this study can result in reductions ranging from 973 - 1227 kg CO_2 eq./MWh for CC and about 2 g CFC-11 eq./MWh for OD. The best-case scenario is the Jatropha biodiesel powered CCGT and the reductions nearly offset the impact of SGE in 5 kVA engines. For further reductions, a small-scale farming approach can be adopted. This ensures an additional 15% and 1% in CC and OD contributions respectively from the LFS cases.

3.1.2. Freshwater and Marine Eutrophication

Eutrophication considers the accumulation of nutrients in the environment and how they affect water quality and the ecosystem [49]. These include direct and indirect effects of the use of fertilisers and chemical substances and emissions of ammonia, nitrates, nitrogen oxides and phosphorous on the ecosystem, a process differentiated into freshwater eutrophication (FE) —Figure 3c and marine eutrophication (ME) —Figure 3d. The use of the reference 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 respectively. These values are minimal with 30 kVA diesel generators —2.41 g P eq./MWh, (FE) and 0.20 kg N 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 substitution with Jatropha biodiesel increases FE and ME, as annual contributions of 283.64 g P eq./MWh (FE), and 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 eq./MWh (ME) for the 30 kVA engines. In embedded power plants, the use of the Jatropha biofuel contributes between 88.70 g P eq./MWh (CCGT) and 134.96 g P eq./MWh (OCGT) to FE. The contributions to ME, on the 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 plants. These contributions to FE and ME from the Jatropha LFS can be reduced significantly by 83% and 96% across all engine types, if small-scale farming systems are adopted. While the impact on marine eutrophication can be reduced below the final values of the reference diesel fuel cases, fresh water eutrophication are 10-11 times more than those of the LFS.

3.1.3. Fossil and Metal Depletion

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

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 observed from Jatropha biodiesel-operated generators (Figure 3f). These values reduced to 4.07 kg Fe eq./MWh in the CCGT but still as much as 6.19 kg Fe eq./MWh for OCGT. All MD values from the Jatropha biodiesel fuel cases are significantly higher than the environmental contributions from diesel powered engines, even in self-generation scenarios.

3.1.4. Ionizing Radiation and Photochemical Oxidant Formation

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

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

3.1.5. Particulate Matter Formation

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

3.1.6. Ecotoxicity and Terrestrial Acidification

Ecotoxicity (ET) accounts for emission of substances that are above the tolerance levels of toxicity and can include human, fresh water, marine, and terrestrial toxicity. This study shows that the use of Jatropha biodiesel has adverse contributions on ecotoxicity, with a range of 8223-16050 kg 1,4-DB eq./MWh depending on engine capacity — Figure 3j. This range is about 21-54% higher than those of the reference diesel fuel in 5 kVA and 30 kVA diesel generators and is as a result of direct application of chemicals, and fertilizers related substances. It also includes the contributions from the use of chemicals for oil conversion processes. The use of the Jatropha biodiesel in embedded 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 kg 1,4-DB eq./MWh (CCGT) annually; however, these values are still twice as much as the reference diesel fuel cases.

In the case of Terrestrial Acidification (TA) as shown in Figure 3k, the contributions include a range between 9.54 and 4.89 kg SO_2 eq./MWh from the consumption of diesel in 5 kVA and 30 kVA diesel generators, values that reduced up to 2.69 kg SO_2 eq./MWh with CCGT operation. The contributions from Jatropha biodiesel fuel consumption were much higher and similar to diesel fuel consumption in self-generation capacities even under best case scenarios with CCGT. The contributions include 28.69 and 4.89 kg SO_2 eq./MWh from Jatropha biodiesel fuel substitution in 5 kVA and 30 kVA diesel generators, as well as 11.34 kg SO_2 eq./MWh, 13.65 kg SO_2 eq./MWh and 8.97 kg SO_2 eq./MWh in 200 kVA diesel, OCGT and CCGT engines respectively. Acid deposition is largely contributed by the emission of acid gases (NOx and SO_2) as well as inputs from fossil energy sources in Jatropha farming and oil conversion processes. Therefore, a small input system can be adopted and this ensures a 20-34% reduction in terrestrial acidification for direct fuel substitution in the different engine cases.

3.2. Sensitivity Analysis

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

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

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.

4. DISCUSSION

Nigeria is considered as one of the least contributor to GHG emissions globally with annual CO_2 emissions of 0.54 tonnes CO_2-eq. per capita [52-53], according to the 2011 World Development Indicators. This ranked the country as the 159th emitter of CO_2 based on emissions per capita, but 39th emitter of CO_2 out of 196 countries based on total CO_2 produced —88 megatonnes in 2011. The country-level rankings were based on the total CO_2 emissions from burning of primary solid, liquid and gaseous fossil fuels including emissions from gas flaring and cement production, but there are no indications that it included emissions from self-generated electricity. To account for SGE, this study estimates a value of 389 million tonnes CO_2 eq. on total CO_2 produced, which corresponds to 2.07 tonnes CO_2-eq. per capita at 2011 estimated population [53]. Thus, in addition to the country-level rankings, Nigeria positions as 112 emitters of CO_2 among the global CO_2 emissions per capita index, and 16th position based on total CO_2 produced. By 2050, Nigeria's population is expected to exceed 400 million [2] and the country can be operating up to a projected 150 million electric generators, if the current practice of SGE persists. This can cause annual GHG emissions of 847 million tonnes CO_2 eq. that places the country potentially as one of the top ten emitters of CO_2.

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

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

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

This study has explored the egalitarian perspective, a choice that assumes the longest time-frame for emission impact in the various environmental mechanisms, as opposed to the short-time frame for the individualist perspective or the dependence on a commonly accepted guidelines for the hierarchist perspective. All the LCA results obtained are thereby worst-case scenarios and exerts prevention as the mitigation strategy or precautionary principle. We have selected the midpoint ReCiPE methodology for characterisation due to the low uncertainties associated with this approach, even in the absence of regional data. Unlike the endpoint approach, this method provides direct and individual environmental contributions without further damage level assessments. With additional and well-structured regional information on the fate and exposure of chemical compounds in the environment, further damage level assessments can be conducted with the mid-point indicators to achieve three end-point indicators (damage to ecosystems, human health and resource availability). The disadvantage of the midpoint approach; however, is that the results are less accessible and difficult to interpret by non-technical audience but the end-point estimations are best suited for well-developed and understood systems and results can be accompanied with large uncertainties.

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

These negative contributions in the Jatropha biodiesel system are resulting from the production and application of synthetic fertilizers, and emissions associated with the use chemicals and fossil fuels in farm equipment and industrial plants. Analysis of the Jatropha biodiesel LFS shows that Jatropha farming is the main cause of emissions in the seven categories including eutrophication, particulate matter formation and terrestrial acidification while oil conversion processes contributed mainly to metal depletion, fossil depletion, photochemical oxidant formation and ecotoxicity. Studies by [19-20,58] attribute the use of nitrogen and phosphate fertilizers and the consumption of fossil derived fuels for the agricultural farming of *Jatropha curcas* has the main contributions to environmental burdens. These fertilizers tend to leak into nearby rivers and streams, and can be released accidentally into the air during application, depending on the soil's properties and environmental conditions. Eshton et al. [20] showed a net GHG contribution of 848 kg t^{-1} from the farming and end-use of Jatropha biodiesel in Tanzania and these were mainly from fertilizer application. From the above studies, Jatropha biodiesel is established as a low-burden and not a burden-free system, due to the inputs of nitrogen and phosphorus fertilizers, and fossil fuels. The use of chemicals such as methanol and sulphuric acid also contributes. Thus, to minimize the negative contributions associated with large-scale system, small-scale farming system can be adopted. While the life cycle impact towards TA, ME and PMF can be minimized beyond those of the reference diesel fuel cases in the SFS, the impact towards FE, MD and ET cannot be minimized. Overall, the magnitude of benefits of the Jatropha biofuel system will largely depend on material inputs, seed yield as well as the environmental status of the reference fuel. Previous studies [59-61] that have examined the LCA of the European standard fuel report GHG emissions in the range of 4.9-24 g CO_2-eq./MJ (well-to-tank analysis), corresponding to 0.34-1.02 kg CO_2-eq./kg. This is less than a third of the value obtained in this study, as such the Jatropha biodiesel system does not have a favorable outcome with a European standard fuel.

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

This study did not associate increased seed yield with increased use of irrigation, fertilizer etc, although seed yield can be linked to improved farming method and inputs. This is because Jatropha farming is yet to be practiced commercially in Nigeria and there is known to what extent that fertilizer use will improve Jatropha seed production. It is also of worth to mention that the scope of the study did not cover social and economic assessment of Jatropha biodiesel production. Land use changes and carbon stock associated with commercial production of the fuel as well as infrastructure development were not considered due to limited local information. The study has only taken into account the main non-CO_2 exhaust emissions (NOx, SOx and CO) which excludes short-lived climate pollutants (SLCPs) such as black carbon (BC), hydrofluorocarbons, volatile organic compounds (VOCs) that are shown in recent times to negatively affect climate change and associated with a number of human respiratory and cardiovascular problems. These SLCPs have a short lifespan of a few days to weeks and varies widely with local conditions. For instance, BC are formed from incomplete combustion of fuels including diesel and biodiesel fuels and from open burning of agricultural waste and wood in cook stoves. Therefore, the inclusion of SLCPs, particularly BC can increase the CC impact of the fuels used in the study. Further work can elaborate on the impact of these compounds. Other aspects that can be investigated which are out of scope of this work is the cost implication of the use of these fuel in diesel engines. Previous studies by the authors [68] showed that the use of the fuels in large industrial gas turbines requires a form of financial instrument to ensure economic viability; hence economic performance analysis will be vital in the light of this environmental assessment. The study has considered the direct substitution of fuels in engines based on the close characteristics of diesel and biodiesel fuels. Since, these fuels have a relatively high biodegradability rate [69], there are possibility for increased maintenance of engines. Such additional environmental impacts and maintenance requirements were not included in the study. For overall life cycle outlook of the Jatropha biodiesel system, further work will aim at expanding the study with socio-economic impact assessment.

5. CONCLUSION

This environmental impacts associated with self-generated electricity and proposed embedded power plants in Nigeria were assessed based on a life cycle perspective. The use of privately-owned diesel powered generators of 5kVA or less can result in annual life cycle GHG emissions of 389 million tonnes CO_2 eq., a value corresponding to 2.07 tonnes CO_2-eq. per capita. This can position the country as the 112 emitters of CO_2 among the global emissions per capita index, and 16th position based on total CO_2 produced. By 2050, the country could be one of the ten emitters of CO_2 if current self-generation activities persist. To satisfy Nigeria's energy demand, there should be a diversification in the energy mix for power generation and a reduction in GHG emissions concurrently. This can be achieved with embedded power plants with Jatropha biodiesel, as the alternative fuel. By substituting the diesel fuel with Jatropha biodiesel, 352 kg CO_2 eq./MWh can be avoided, a 22% reduction. Further reductions in CC of up to 76% can be achieved with embedded power generation. Such projects can significantly reduce the environmental impact of self-generated electricity across most impact categories, however at a cost on terrestrial acidification, metal depletion, freshwater- and marine-eutrophication. These contributions are resulting from the production and application of synthetic fertilizers, and emissions associated with the use chemicals and fossil fuels in farm equipment and industrial plants. An adoption of a small-scale farming approach, the reduction of fertilizer and chemicals at the cost of yield and the replacement of fossil fuels with renewable options can further reduce the contributions from the Jatropha biodiesel system.

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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	km	100
(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_2 exhaust emissions from different power plants [28, 39-40]

Engine/Fuel Type	Diesel Engine		Gas Turbine	
Emissions	Diesel	Jatropha Biodiesel	Diesel	Jatropha Biodiesel
CO	3.69E-03	1.76E-05	7.92E-06	4.40E-06
NOx	1.58E-05	7.92E-04	3.52E-04	5.28E-04
SOx	2.67E-02	-	2.12E-03	-

Table 3-Inventory for Jatropha biodiesel System

SUB-PROCESSES	SMALL-SCALE FARMING	LARGE-SCALE FARMING
PRE-NURSERY		
Seeds for Nursery	0.769 g $seed^{-1}$	0.769 g $seed^{-1}$
Water for Nursery	0.2 L $seed^{-1}day^{-1}$/60 days	0.2 L $seed^{-1}day^{-1}$/60 days
Polyethylene Bags (Nursery)	2 g bag^{-1}	2 g bag^{-1}
Human Labour	1 man day^{-1}/60 days	1 man day^{-1}/60 days
FIELD PREPARATION		
Tractor Use for Land Preparation	5 men ha^{-1} day^{-1}/5 days	45 L diesel $ha^{-1}run^{-1}$
Weeding/Fertilizer Application	5 men ha^{-1} day^{-1}	12.5 L diesel $ha^{-1}run^{-1}$
Harvesting	50 kg dry seed $man^{-1}day^{-1}$	50 kg dry seed $man^{-1}day^{-1}$
Fertilizer, N	-	121.48 kg $ha^{-1}yr^{-1}$
Fertilizer, P_2O_5	-	46.49 kg $ha^{-1}yr^{-1}$
Fertilizer, K_2O	-	133.47 kg $ha^{-1}yr^{-1}$
Compost	0.5 kg $pit^{-1}yr^{-1}$	-
Glyphosphate (Herbicide)	3 L $ha^{-1}yr^{-1}$	3 L $ha^{-1}yr^{-1}$
Paraquat (Herbicide)	2 L $ha^{-1}yr^{-1}$	2 L $ha^{-1}yr^{-1}$
Insecticide	0.04 g $plant^{-1}yr^{-1}$	0.04 g $plant^{-1}yr^{-1}$
Gasoline Use (Extra)	40 L $ha^{-1}yr^{-1}$	40 L $ha^{-1}yr^{-1}$
Diesel Use (Extra)	60 L $ha^{-1}yr^{-}$	60 L $ha^{-1}yr^{-}$
Transportation (To Crushing Site)	50 km @20mpg	50 km @20mpg
Water for Insecticide Application	100 L	100 L
Diesel for Irrigation	-	60 L ha^{-1}
Irrigation	-	8 L $plant^{-1}week^{-1}$
Transport for Irrigation	-	43 km @20 mpg
OIL EXTRACTION		
Cracking Machine	2hp@100 kg hr^{-1}	2hp@100 kg hr^{-1}
Expeller	37.5hp@ 0.75 ton hr^{-1}	37.5hp@ 0.75 ton hr^{-1}
Filtering Machine	2hp@160L hr^{-1}	2hp@160L hr^{-1}
Transportation (Crushing Site to Biodiesel Plant)	40 km@ 20 mpg	40 km@ 20 mpg
OIL CONVERSION		
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

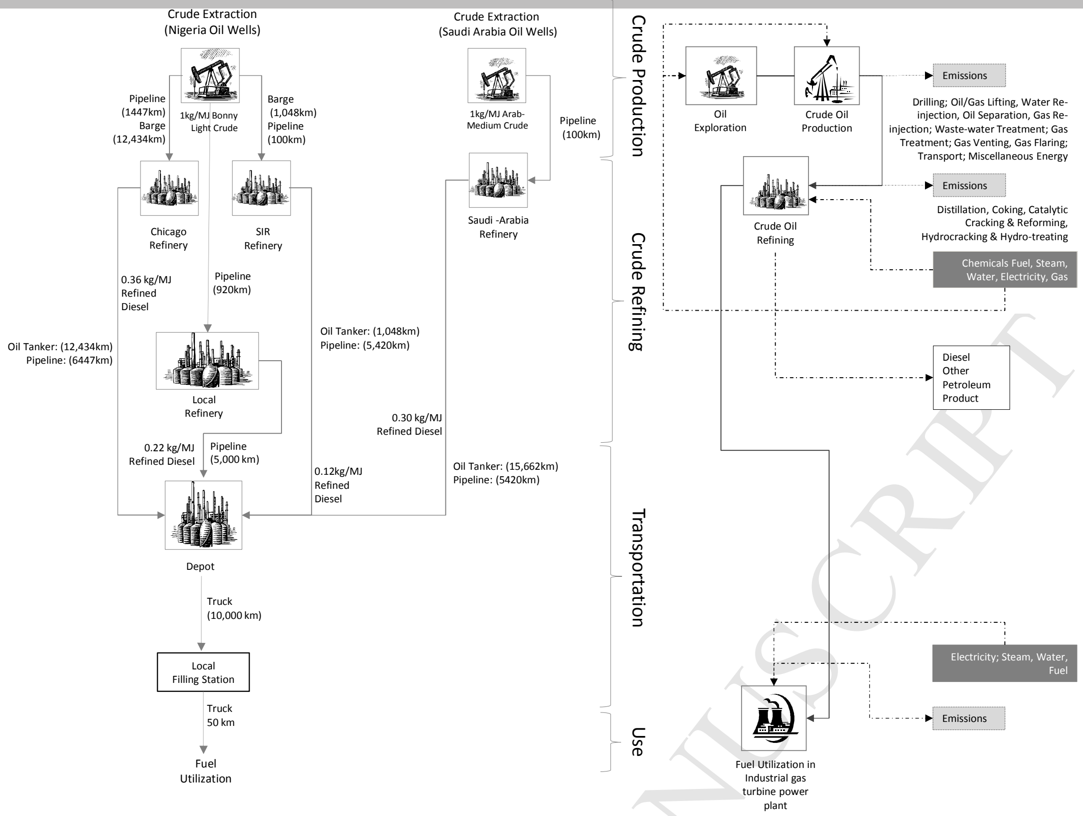


Fig. 1: Description/System Boundary for the Reference Diesel System

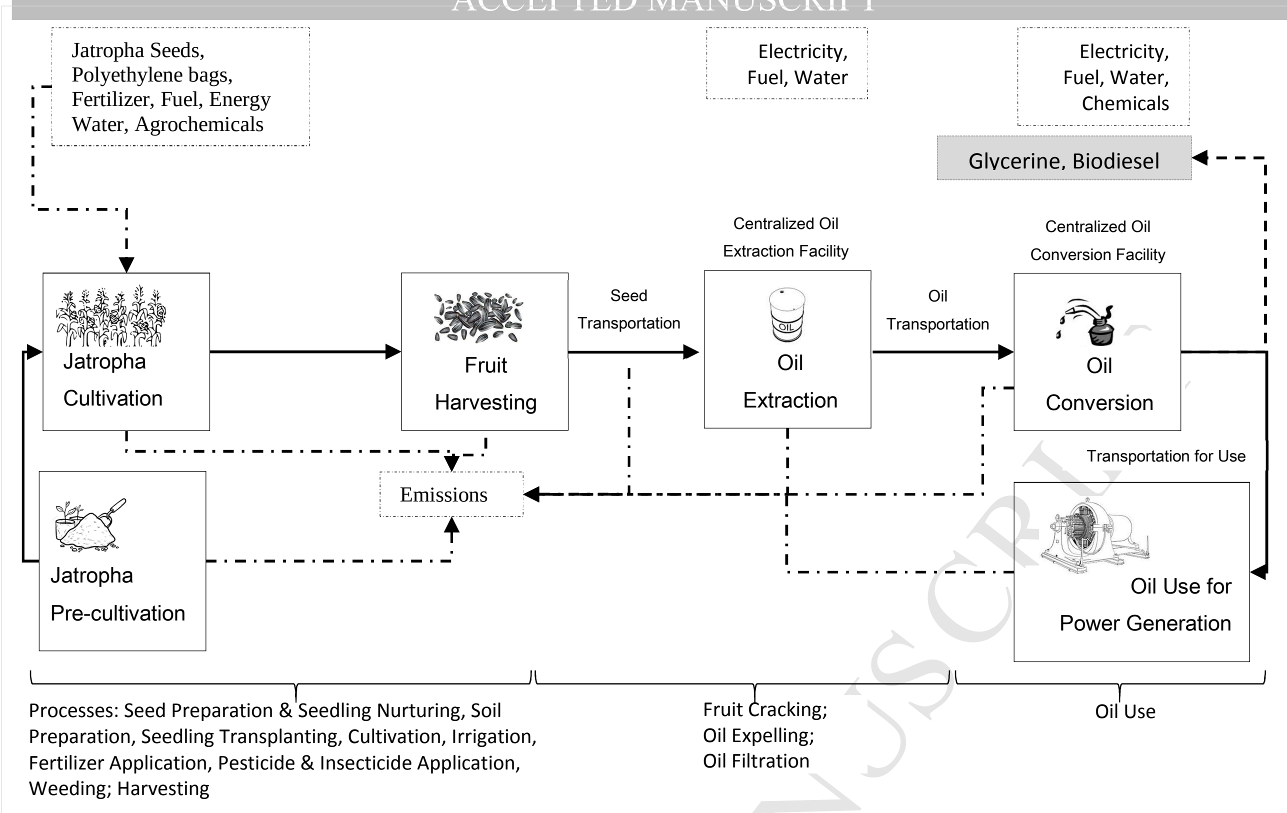
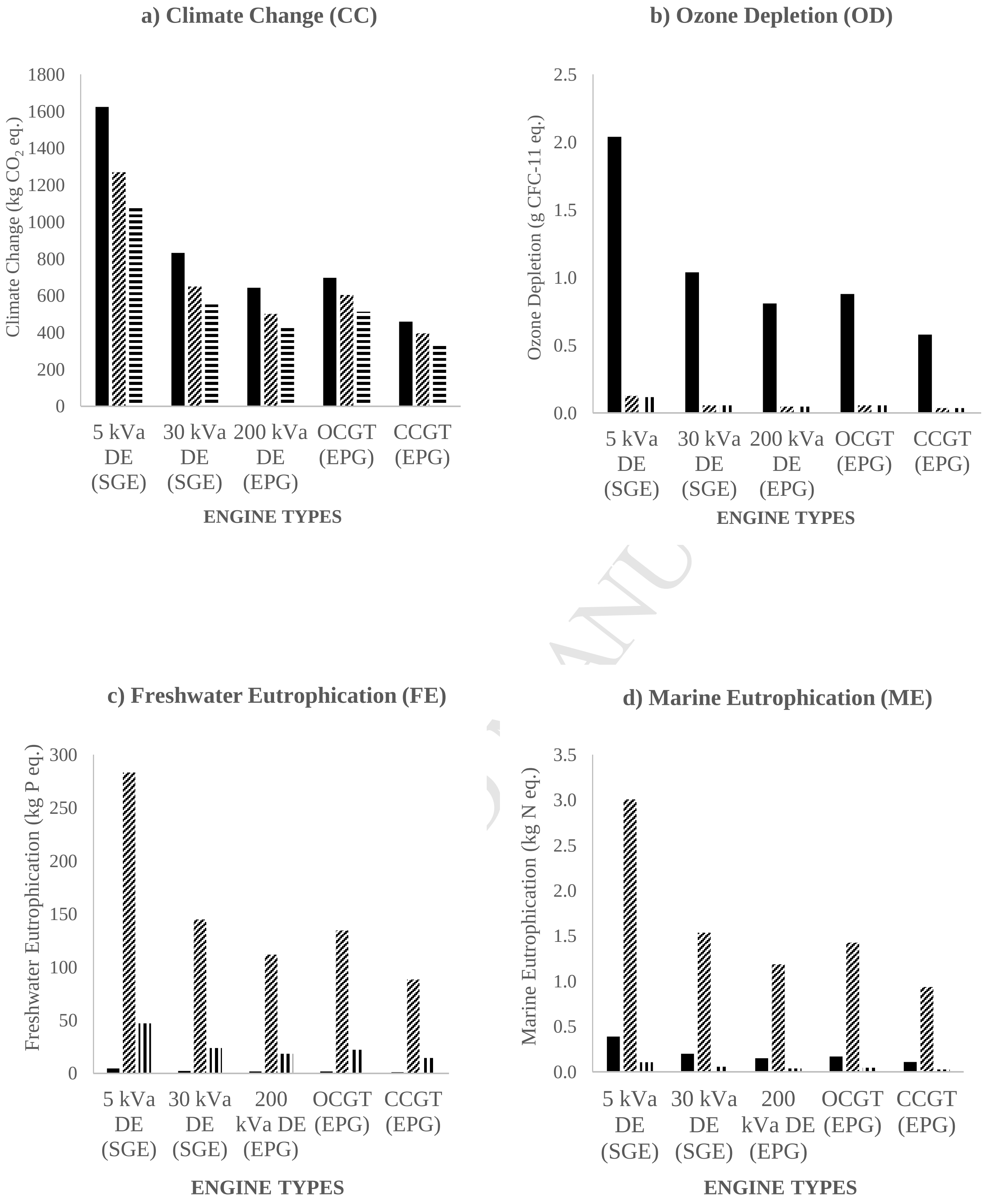
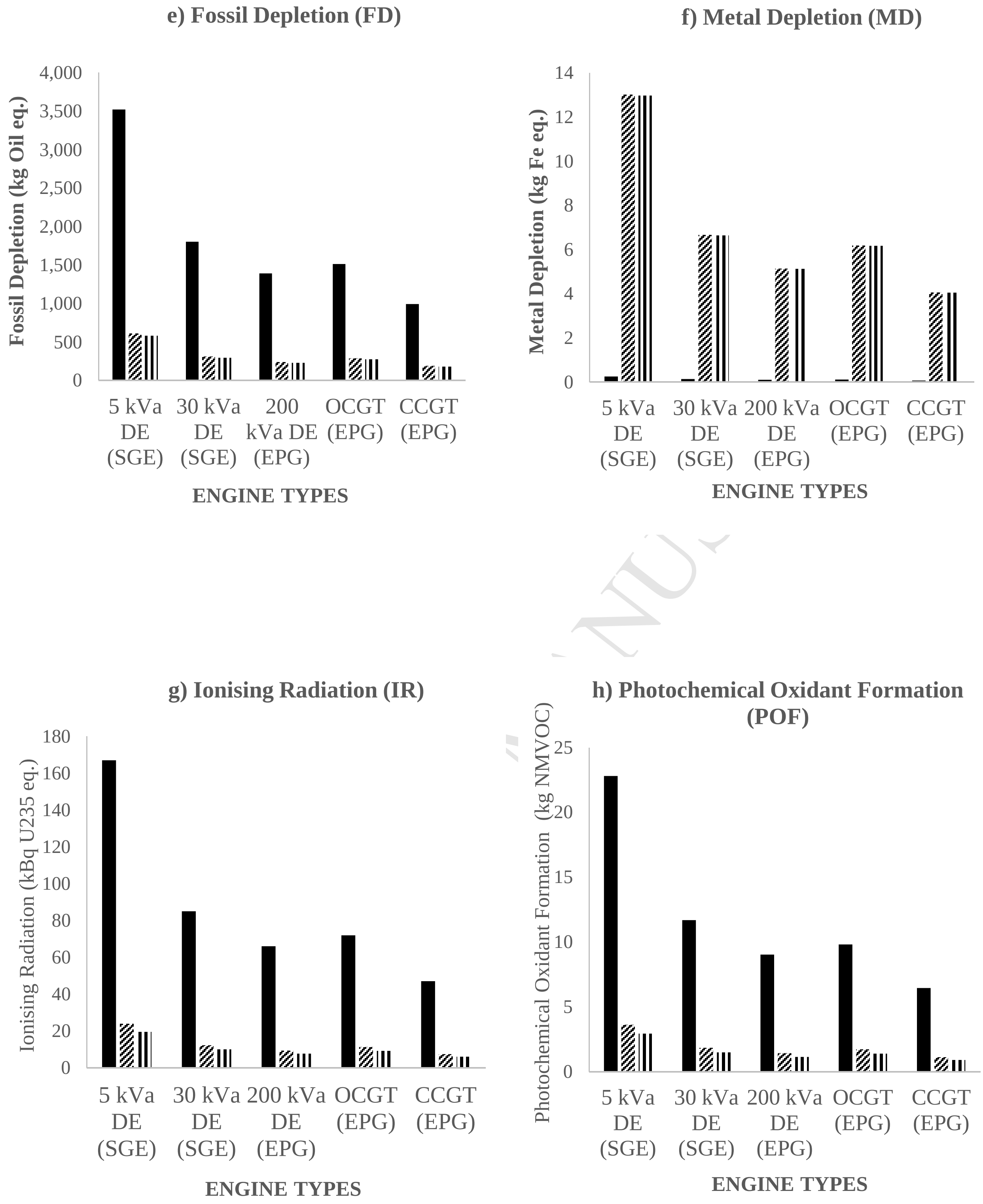
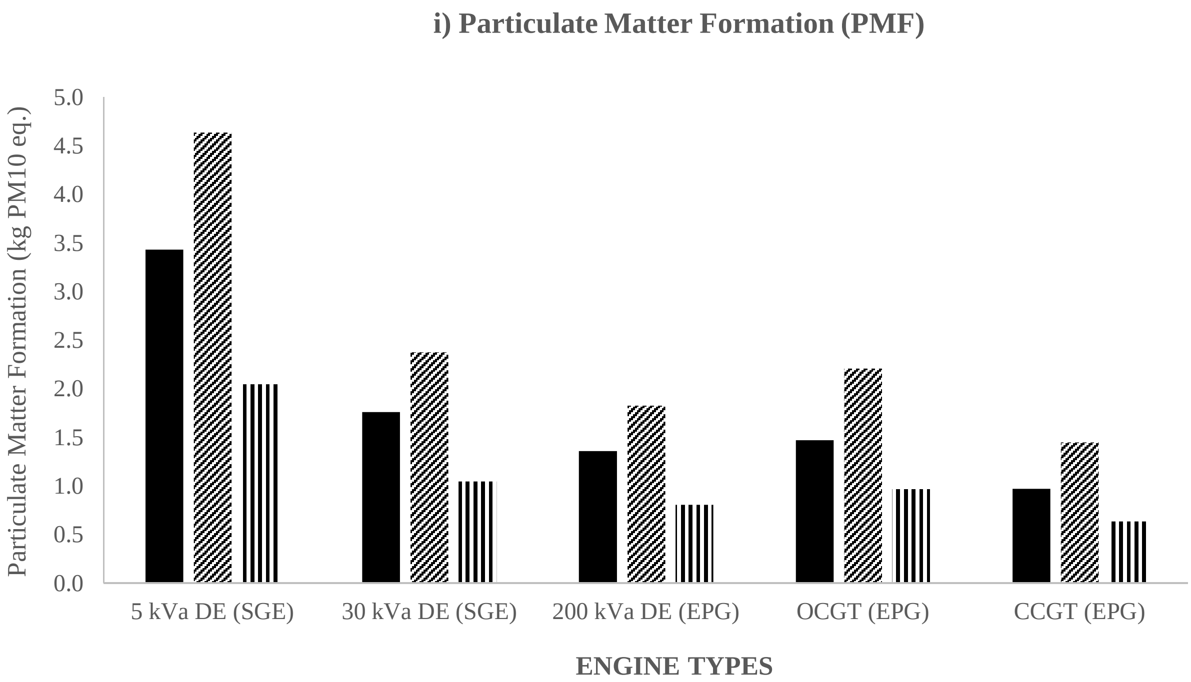


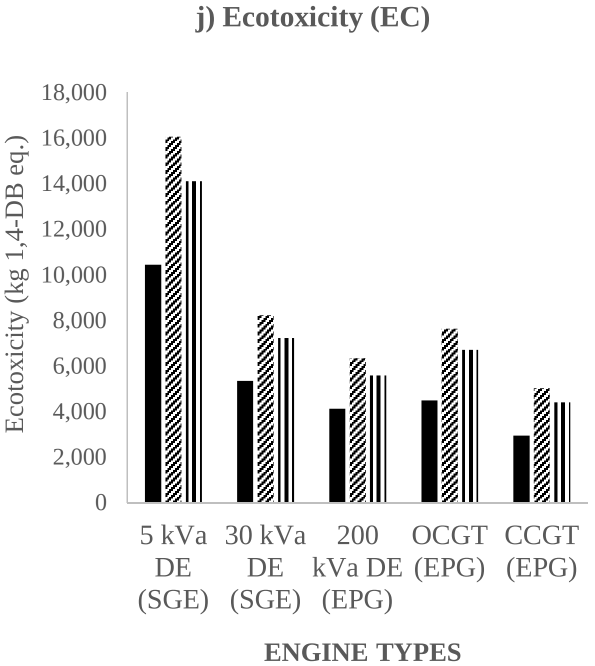
Fig. 2: Description/System Boundary for the Jatropha biodiesel System



a) Climate Change (CC)
Climate Change (kg CO2 eq.)
1800
1600
1400
1200
1000
800
600
400
200
0
5 kVa DE (SGE)
30 kVa DE (SGE)
200 kVa DE (EPG)
OCGT (EPG)
CCGT (EPG)
ENGINE TYPES
b) Ozone Depletion (OD)
Ozone Depletion (g CFC-11 eq.)
2.5
2.0
1.5
1.0
0.5
0.0
5 kVa DE (SGE)
30 kVa DE (SGE)
200 kVa DE (EPG)
OCGT (EPG)
CCGT (EPG)
ENGINE TYPES
c) Freshwater Eutrophication (FE)
Freshwater Eutrophication (kg P eq.)
300
250
200
150
100
50
0
5 kVa DE (SGE)
30 kVa DE (SGE)
200 kVa DE (EPG)
OCGT (EPG)
CCGT (EPG)
ENGINE TYPES
d) Marine Eutrophication (ME)
Marine Eutrophication (kg N eq.)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
5 kVa DE (SGE)
30 kVa DE (SGE)
200 kVa DE (EPG)
OCGT (EPG)
CCGT (EPG)
ENGINE TYPES


e) Fossil Depletion (FD)
Fossil Depletion (kg Oil eq.)
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
5 kVa DE (SGE)
30 kVa DE (SGE)
200 kVa DE (EPG)
OCGT (EPG)
CCGT (EPG)
ENGINE TYPES
f) Metal Depletion (MD)
Metal Depletion (kg Fe eq.)
14
12
10
8
6
4
2
0
5 kVa DE (SGE)
30 kVa DE (SGE)
200 kVa DE (EPG)
OCGT (EPG)
CCGT (EPG)
ENGINE TYPES
g) Ionising Radiation (IR)
Ionising Radiation (kBq U235 eq.)
180
160
140
120
100
80
60
40
20
0
5 kVa DE (SGE)
30 kVa DE (SGE)
200 kVa DE (EPG)
OCGT (EPG)
CCGT (EPG)
ENGINE TYPES
h) Photochemical Oxidant Formation (POF)
Photochemical Oxidant Formation (kg NMVOC)
25
20
15
10
5
0
5 kVa DE (SGE)
30 kVa DE (SGE)
200 kVa DE (EPG)
OCGT (EPG)
CCGT (EPG)
ENGINE TYPES





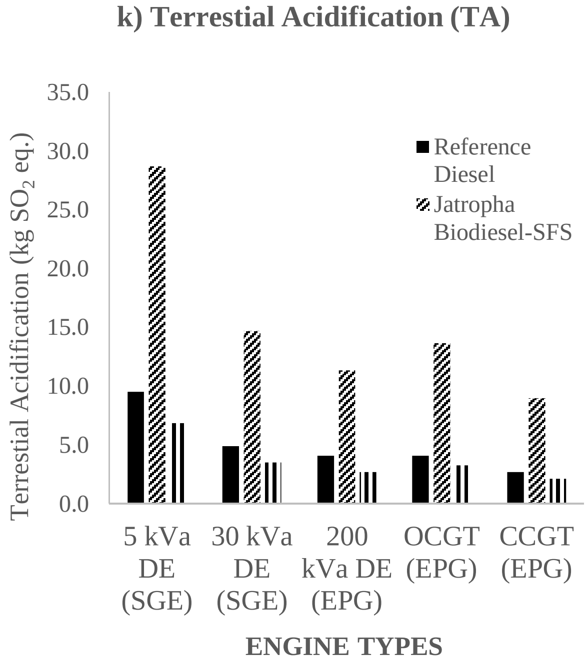
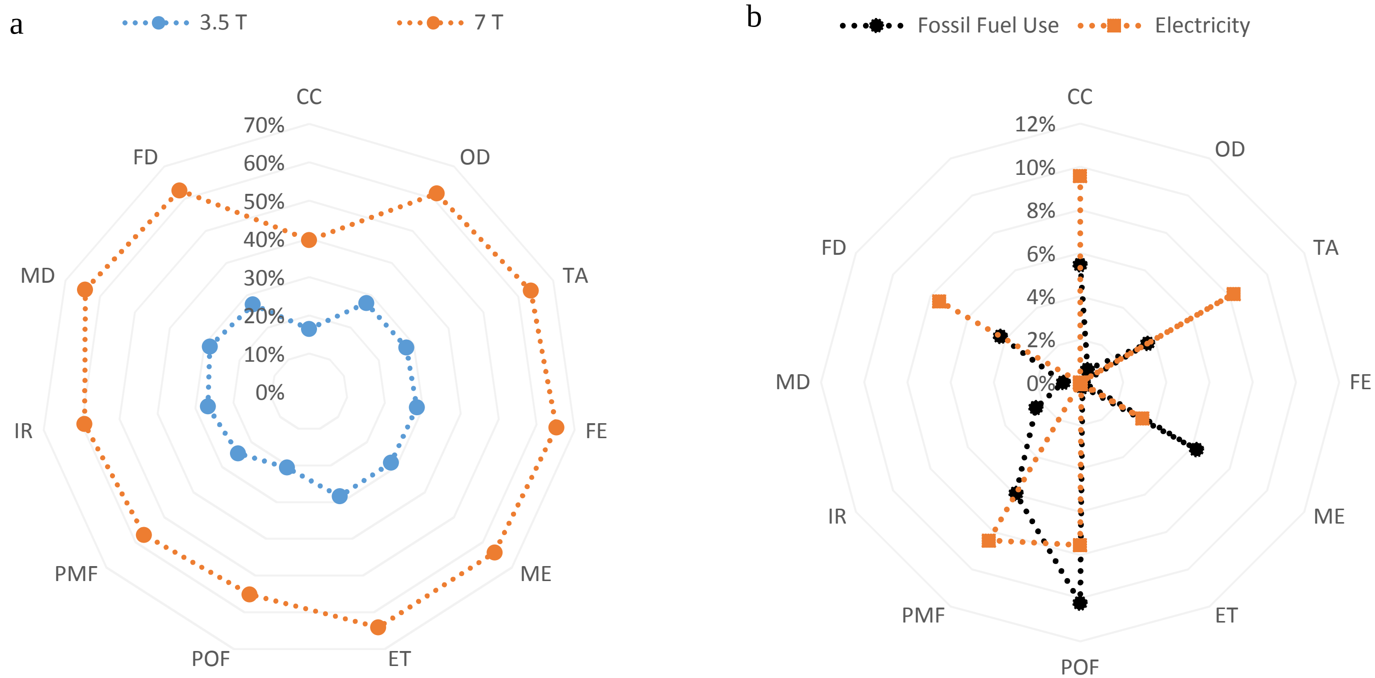


Figure 3a-k: Environmental Contributions as a Function of fuel types, farming systems and engine application: a) Climate Change, b) Ozone Depletion, c) Freshwater Eutrophication, d) Marine Eutrophication, e) Fossil Depletion, f) Metal Depletion, g) Ionising Radiation, h) Photochemical Oxidant Formation,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


a
3.5 T
7 T
CC
OD
TA
FE
ME
ET
POF
PMF
IR
MD
FD
70%
60%
50%
40%
30%
20%
10%
0%
b
Fossil Fuel Use
Electricity
CC
OD
TA
FE
ME
ET
POF
PMF
IR
MD
FD
12%
10%
8%
6%
4%
2%
0%

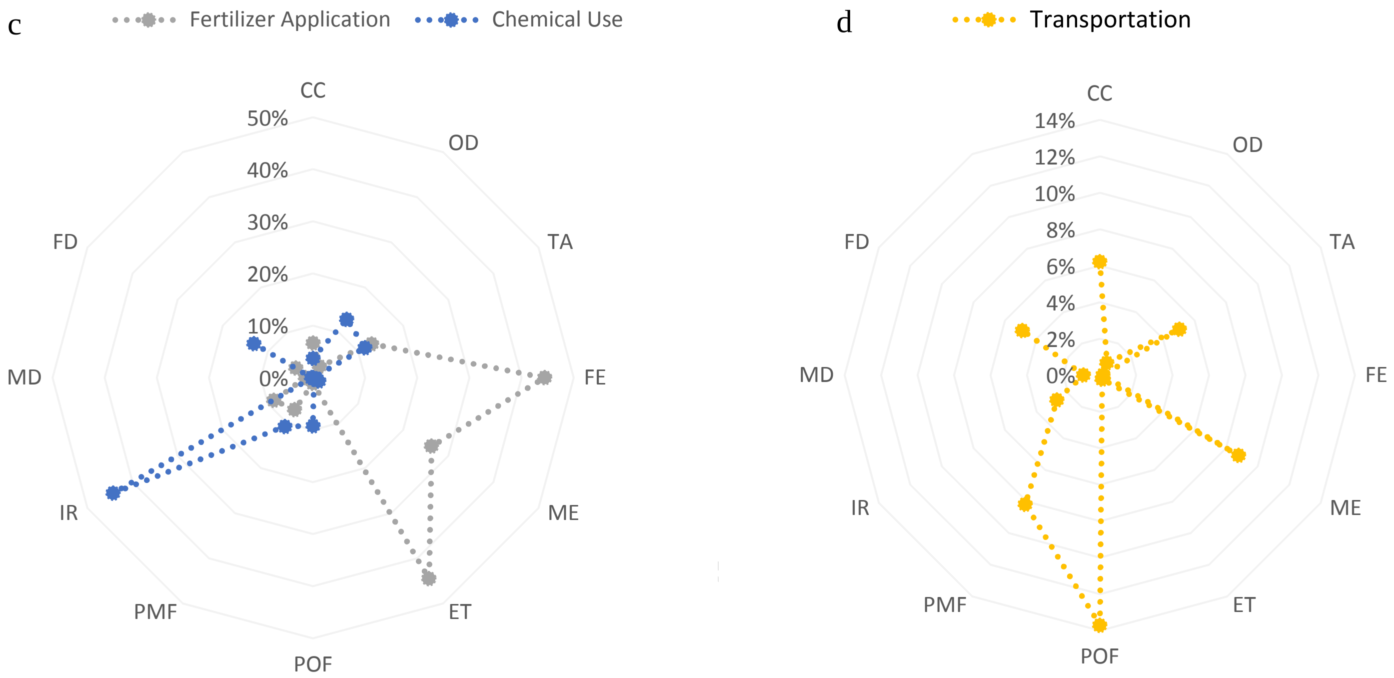


Figure 4a-d: Radar chart of the sensitivity analysis: a) seed yield, b) fossil fuel use and electricity, c) fertilizer application and chemical use and d) transportation of Jatropha seeds, oil and biodiesel fuel.

Highlights

- Self-generated electricity (SGE) contributes of 1625 kg CO_2 eq./MWh of electricity
- SGE in Nigeria contributes 389 million tonnes CO_2 eq. annually to climate change
- This can rank Nigeria in the top 20 on the global CO_2 emission index
- Jatropha biodiesel in embedded power plants can reduce CO_2 emissions by 22-76%
- Magnitude of benefits depends on plant yield, farming system and engine efficiency