Renewable and Sustainable Energy Reviews 63 (2016) 172–192

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Biomass resources and biofuels potential for the production of transportation fuels in Nigeria

Juliet Ben-Iwo, Vasilije Manovic, Philip Longhurst

Cranfield University, Bedford MK43 0AL, United Kingdom

ARTICLE INFO

Article history:
Received 5 July 2015
Received in revised form
7 February 2016
Accepted 2 May 2016

Keywords:
Bio-refineries
CO_2 emissions
Energy
Feedstock
Production

ABSTRACT

Solid biomass and waste are major sources of energy. They account for about 80% of total primary energy consumed in Nigeria. This paper assesses the biomass resources (agricultural, forest, urban, and other wastes) available in Nigeria and the potential for biofuel production from first, second, third and fourth generation biomass feedstocks. It reviews the scope of biomass conversion technologies tested within the country and the reports on the technology readiness level of each. Currently, most of the emerging biofuels projects in Nigeria utilize first generation biomass feedstock for biofuel production and are typically located many miles away from the petroleum refineries infrastructures. These feedstocks are predominantly food crops and thus in competition with food production. With significant availability of non-food biomass resources, particularly in the Niger Delta region of Nigeria, and the petroleum refineries located in the same area, it is pertinent to consider expanding use of the petroleum refinery's infrastructure to co-process non-food biomass into bio-intermediate oil for blending with petroleum. This not only addresses the potential food versus fuel conflict challenging biofuel production in Nigeria, but also reduces the cost of setting up new bio-refineries thus eliminating the transportation of ethanol to existing petroleum refineries for blending. In view of this, it is recommended that further research be carried out to assess the feasibility of upgrading existing refineries in Nigeria to co-process bio-based fuels and petroleum products thus achieving the targets set by the Nigeria Energy Commission for biofuel production in the country.

Contents

E-mail address: p.j.longhurst@cranfield.ac.uk (P. Longhurst).

http://dx.doi.org/10.1016/j.rser.2016.05.050

1. Introduction

The combustion of fossil fuels such as coal, oil and natural gas for the conventional method of producing transportation fuels, chemicals, and power, has been established for many years [1]. This method is a significant global concern as it releases greenhouse gases (GHG) particularly carbon dioxide (CO_2) into the atmosphere. Petroleum consumption for road transportation is currently the largest source of CO_2 emissions [2]. It accounts for 23% of CO_2 emissions worldwide [3] and 59.5% of CO_2 emissions in Nigeria [4].

In 2013, world CO_2 emissions from the consumption of petroleum exceeded 11,830 million metric tonnes [5] World total transport energy use and CO_2 emissions are projected to be 80% higher by 2030 than the current levels [3]. The United States Environmental Protection Agency (US-EPA) cited in [6] calculated the amount of CO_2 emissions from the combustion of gasoline and diesel to be about 8.887×10^{-3} and 1.0180×10^{-2} metric tonnes CO_2/gallon respectively. According to Howey et al. [7] unless there is a switch from fossil fuel to low-carbon alternative fuel, CO_2 emissions from vehicles may not reduce below ~8 kg CO_2.

One major method which has been studied to reduce CO_2 emissions from vehicles is the blending of gasoline with ethanol [6]. It is estimated that about 8.908×10^{-3} metric tonnes of CO_2 are emitted from the combustion of a gallon of gasoline that does not contain ethanol, and 1.015×10^{-2} metric tonnes of CO_2 are emitted from the combustion of a gallon of diesel that does not contain ethanol [8]. Increase in the consumption of ethanol fuel has mitigated increases in CO_2 emissions from the transportation sector [9]. To further reduce these emissions, fuel switching to low carbon alternatives such as biomass fuel is essential. This is because, biomass currently offers the only renewable source of energy that can substitute for petroleum fuels as well as reduce CO_2 emissions [10,11].

Globally, biomass fuel is becoming ever more attractive as suitable substitute for fossil fuels due to the increasing demand for clean energy, declining fuel reserves, and its contribution towards reducing dependence on crude oil. The processing of biomass for biofuel, biopower, and bioproducts has important effects on international policy and economy, and on rural development. It reduces the dependence on oil-producing countries and supports rural economies by creating jobs and providing an additional source of income [12]. Hence the purpose of this review.

Despite Nigeria having four petroleum refineries with combined crude distillation capacity of 10.7 million barrels per day (bbl./d) [13], an amount that far exceeds the national demand, the country still imports the majority of refined petroleum products. This is due to the low capacity utilization of existing refineries [13]. At 2013, typical capacity utilization for the four existing refineries was about 22%, with crude oil production of 2367 thousand bbl./d. At the same time, approximately 164,000 bbl./d of petroleum, and 82,000 barrels of fuel ethanol were imported [13]. To reduce the nation's dependence on imported oil it is important to improve refinery utilization and diversify to other energy resources. Therefore the development of alternative fuels particularly biomass-derived fuels from locally available biomass needs investigation.

There is a wide range of biomass conversion processes, at varying stages of technical maturity. Some are commercially available, while others are at demonstration stages. For instance, ethanol production from sugar cane is commercially available in Brazil [14], while biofuel production from algae is at research and development phase [15]. Existing research on biomass resources and the potential for biofuels in Nigeria is focused on power generation and biofuels production from first generation biomass. Typically this substitutes fuel production for food crops. There is currently limited information on the state of biomass conversion technologies for the utilization of non-food crops for transportation fuels production in Nigeria.

This paper reviews biomass resources and biofuel potentials to produce transportation fuels, notably biomass resources available from first, second, third and fourth generation feedstocks in Nigeria. It assesses the biomass conversion technologies tested in the country, and the technology readiness level. It also identifies research gaps alongside the policy targets defined for sustainable biofuel production. In addition, the potential for biofuel contributing towards more sustainable production with improved environmental and socio-economic benefits is discussed. More detailed region-specific evaluation of biomass resources can then be used to define the scope for local production of biofuels within Nigeria.

2. Biomass resources in Nigeria

The term biomass literally means living matter. However, biomass is often used to describe any organic material obtained from plant and animal tissue [16]. This includes agricultural resources, agricultural residues, forest resources, waste including municipal solid waste, industrial waste, and other wastes, as well as algae. These materials are referred to as feedstocks in bio-refining and are classified into four generations: first, second, third, and fourth. First generation refers to the biofuels derived from agricultural products: sugar or starch-based crops and oilseeds, e.g. sugarcane to produce bioethanol or palm oil for the production of biodiesel. Through fermentation or trans-esterification, first generation biomass feedstocks can be processed into bioethanol or biodiesel respectively. Most common uses are as first generation biofuels.

Biomass is abundant in nature and broadly dispersed globally with its distribution being dependent on geographical area. Countries such as Brazil and Nigeria have significant natural resources to produce transportation biofuels, biopower and bioproducts from biomass. Nigeria has substantial biomass potential of about 144

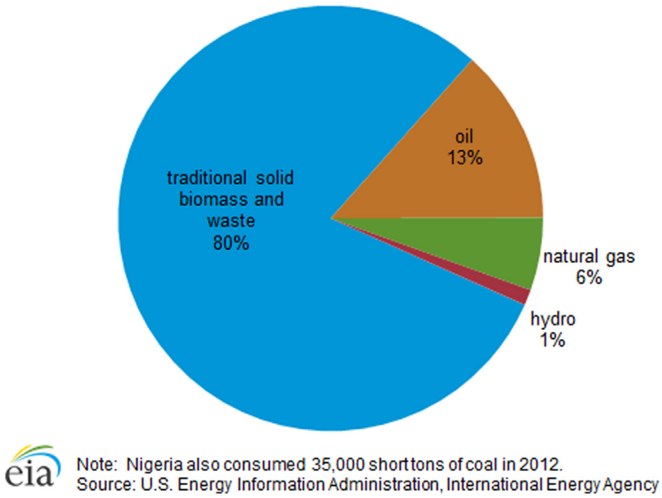

Fig. 1. Total energy consumption in 2012 [13].

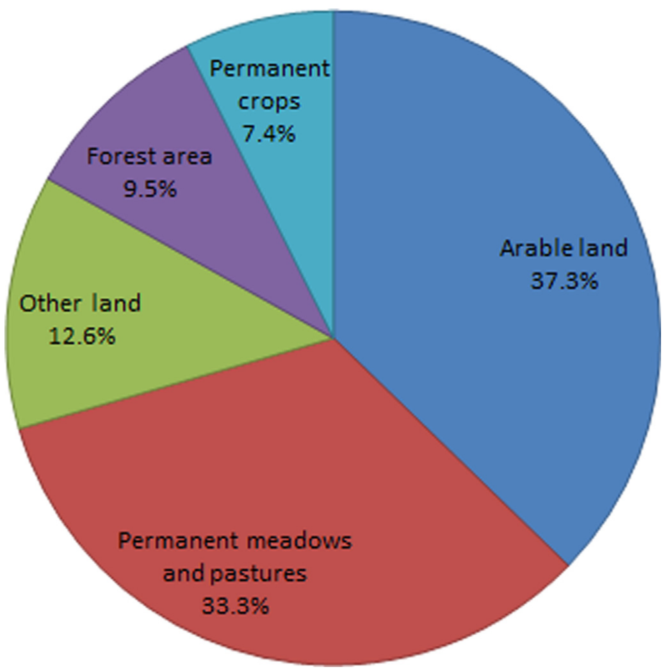

Fig. 2. Nigeria land use in 2011 (latest update: 2015). Last accessed on 17th January 2016. URL: http://faostat3.fao.org/browse/area/159/E [20].

million tonnes per year [17]. According to the U.S. Energy Information Administration [13] most Nigerians, especially rural dwellers, use biomass and waste from wood, charcoal, and animal dung, to meet their energy needs. Biomass (comprising crop residues, manure, charcoal, and wood) accounts for about 80% of the total primary energy consumed in Nigeria [13]; oil (13%), natural gas (6%) and hydro (1%) [13]. This large percentage represents biomass used to meet off-grid heating and cooking needs in the rural areas (Fig. 1).

The total land area of Nigeria is approximately 92,376,000 ha (ha), and is divided into 36 states [18] with available land area of about 91,077,000 ha. Of this agriculture covers 71,000,000 ha [19]. About 37.3% of the agricultural area is arable land, i.e. 7.4% permanent crops and 9.5% forest areas, Fig. 2, indicating a large share of cultivatable land for biofuel production in the country.

As at 2014, the population of Nigeria was 178,517,000 with a density of 193.2 inhabitants per km^2 [21]. Rural dwellers account for about 50% of the population [22]. The country Gross Domestic Product (GDP) at market prices was estimated at US$568.5 billion in 2014 [23], and annual growth rate at 6.3% [24] of which the agricultural sector contributes about 4.3%. A total of 12.6 million economically active people are engaged in agriculture [21]. The national poverty level in 2009 was 46%, with the human development index at about average in 2013 [23] providing a significant and growing demand for energy (Table 1).

Table 1
Country statistics and population [21,23,24].

Parameter	Year	Value	Unit
Population	2014	178,517	1000
Population density	2014	193.2	Inhabitants/km^2
GDP at market price	2014	568.5	billion US$
Annual GDP growth rate	2014	6.3	%
Agriculture, value added to GDP	2014	4.3	%
Total population of economically active	2014	21.97	%
Population economically active in agriculture	2014	12 577	1 000 inhabitants
Poverty head count at national poverty line	2009	46	% of population
CO_2 emissions from consumption of fossil fuels	2012	86.4	Million metric tons CO_2
CO_2 emissions from consumption of petroleum	2013	43.77	Million metric tons CO_2
Total Primary Energy production	2012	6.692	Quadrillion Btu
Total Primary Energy consumption	2012	4.5	Quadrillion Btu
Crude oil production	2013	2 367.37	Thousand bbl./d
Petroleum consumption	2013	302	Thousand bbl./d
Petroleum Import	2013	164	Thousand bbl./d

Btu – British thermal unit; bbl./d – barrels per day; GDP – Gross Domestic Product; Percentage – %.

Biomass feedstocks can be converted into different fuels using a range of processes to generate heat or electricity, produce liquid biofuels, or biogas. Most of the emerging bio-refineries in Nigeria use first generation biomass feedstocks (Fig. 3). These sources are largely food crops and thus not sustainable for biofuel production. First generation bio-refining is largely driven by legislative targets and favourable taxation to increase biofuel supply Most notable is the directives set by the EU (2009/28/EC), the US Energy Independence and Security Act of 2007 [25], and the 2005 Nigerian Biofuel Policy Incentive which sets legislative targets for establishing biofuel markets by providing exemptions for biofuel industries from taxation [26].

The adverse effects first generation biomass feedstock have on global food prices is moving research into the use of lignocellulosic biomass resources, otherwise known as second generation biomass feedstocks. These feedstocks include crop residues, wood residues and dedicated energy crops cultivated primarily for the purpose of biofuel production. Second generation biomass feedstocks are increasingly gaining interest globally as sustainable alternative to fossil fuels because they are not food crops and so not in competition with food [27].

There is a wide variety of photosynthetic and fermentative bacteria and algae that are currently being explored as biocatalysts for biofuel production because of their high carbohydrate or lipid/oil contents. These microbial cells are categorised as third-generation biomass feedstock [28]. In comparison to first- and second-generation feedstock for biofuel production, these microbial cells are more sustainable because, they do not require arable crop lands or other farming inputs (such as fertilizers, pesticides, and water) for cultivation, and so are not in competition with food.

Algae have a fast growth rate compared to other terrestrial plants and can grow in different liquid media – wastewater streams (saline/brackish water/coastal seawater) which are common in the Niger Delta region of Nigeria. Algae can also be

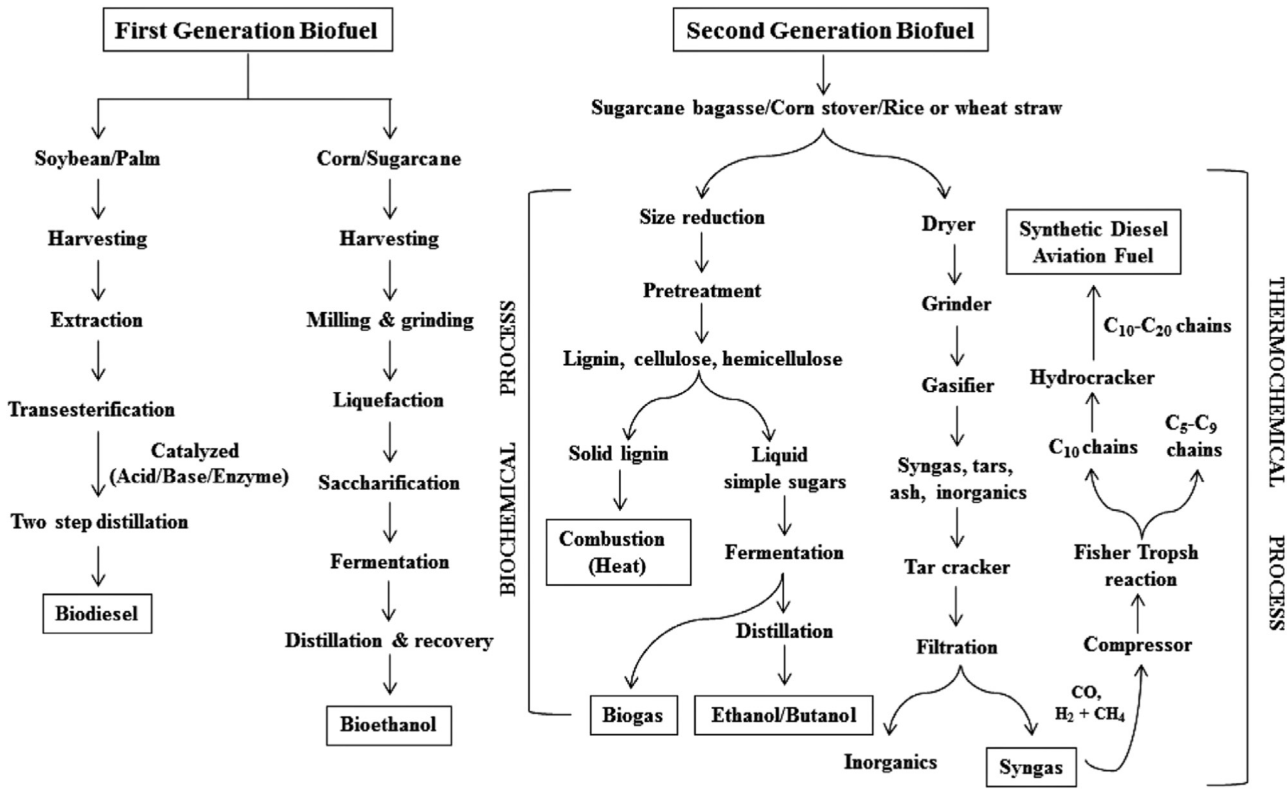

Fig. 3. First and second generation biofuels [28].

cultivated in high yields using bioreactors. It is estimated that microalgae could produce about 10 to 300 times more oil (for biodiesel) than traditional or dedicated energy crops in future [28]. However, the algal-based oil production platform is technologically immature.

Biofuels from third generation sources have limitations in terms of economic performance, ecological footprint, reliance on sunlight, geographical location and so are inadequate to substitute for fossil fuels [28].Metabolic engineering involving biosynthesis can improve alcohol productivity. This process is categorised as fourth generation bio-refining (Fig. 4). Genetic modification can be used to increase CO_2 capture and lipid production as well as develop low input, fast growing energy crops with reduced fertilizers, insecticides, and water requirements. For instance, genetically modified wheat and barley contain more hydrolysable biomass [28]. Advanced biofuels such as biobutanol and biomethane are gaining as much investment support currently as bioethanol, due to their high energy density, low hygroscopic and less corrosive nature.

2.1. Agricultural resources in Nigeria

Biomass feedstocks can be grouped into: agricultural resources, crop residues, forestry resources, urban waste and other waste. The Nigerian agricultural sector is characterized by traditional smallholders, who use simple production techniques and bush-fallow systems for cultivation [22,29]. However, this accounts for about two-thirds of the country's total agricultural production [29]. Prior to the discovery of oil and gas, agriculture was the mainstay of the nation's economy [30]. It accounts for over 50% of the GDP and 75% of export revenue [29]. But with the rapid growth of the petroleum industry, there has been gross neglect in agricultural development, and this has led to a relative decline in the sector.

Agriculture in Nigeria is also influenced by the climatic and vegetative zones. Nigeria is classified into eight agro-ecological zones (Table 2) based on the temperature and rainfall pattern from the north to the south. The variation in rainfall, temperature, and humidity, and its effect on the natural vegetation zones determines the types of indigenous plants that are grown in the country. Apart from the ultra-humid belt along the coast which has an average rainfall of 2,000 mm/year, the climate in the north is semi-arid, while that of the south is humid [22]. The humid tropical zone favours the growth of low base saturation and low solar radiation crops such as cassava, rice, sweet potatoes, and some grasses [29].

The ecological zones are distinguished by the northern Sudan Savannah, southern rain forest, and Guinea Savannah or Middle belt [22]. The savannah land represents 80% of the vegetation zones, and serves as natural habitat for grazing large numbers of livestock such as camels, cattle, donkeys, goats, horses, and sheep [29]. The humid tropical forest zone in the south which has longer rains when compared to the savannah land in the north, has the capacity of supporting plantation crops such as cocoa, coffee, cotton, oil palm, rubber, and staple crops like cassava, cocoyam, cowpeas, groundnut, maize, melon, rice, sweet potatoes, and yam [29].

The increasing rainfall from the semi-arid north to the tropical rain forest south also allows for crop diversity, from short season cereals, millet, sorghum, and wheat in the north to cassava, rice, and yams in the wet zones. Cash crops such as cotton, groundnuts and tobacco are grown in the drier north, while cocoa, coffee, ginger, rubber, sugar, and oil palm are grown in the south [29].

2.1.1. Energy crops

Energy crops such as sugarcane, cassava, sweet sorghum, and corn are plants with high energy content that can be grown specifically as biomass feedstock [25,32]. They can be grown on marginal or degraded agricultural land. However, their growth is also based on rainfall distribution. Nigeria has huge potential for

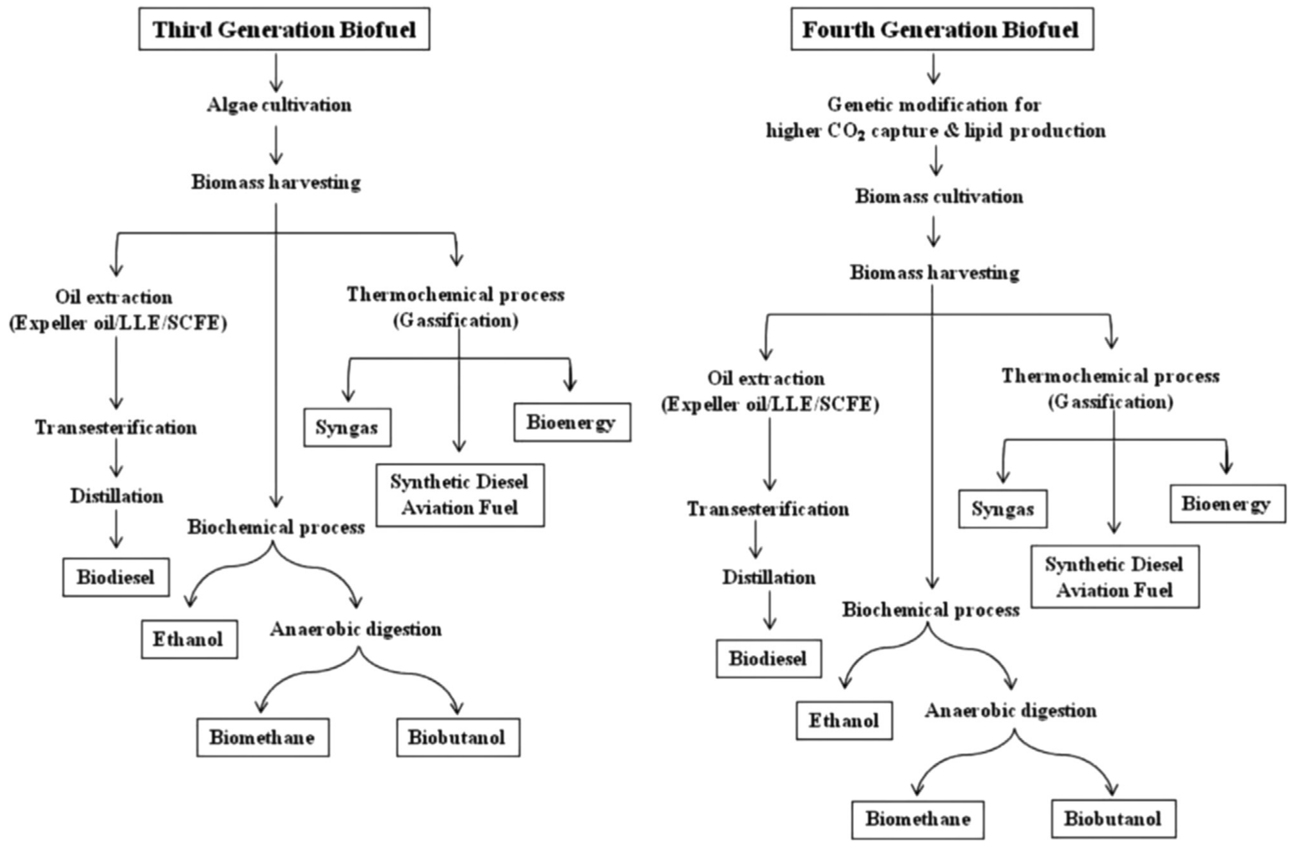

Fig. 4. Third- and fourth generation biofuels [28].

Table 2
Nigeria's agro-ecological zones [22,29,31].

Zones description	Percentage of country area (%)	Annual rainfall (mm)	Monthly temperature (°C)			Major crops
			Min	Normal	Max	
Semi-arid	4	400–600	13	32–33	40	Sorghum, millet, wheat
Dry sub-humid	27	600–1000	12	21–31	49	Sorghum, taro, maize, cassava, rice, millet, yam
Sub-humid	26	1000–1300	14	23–30	37	Sorghum
Humid	21	1100–1400	18	26–30	37	Yam, cocoyam, cassava, rice, maize
Very humid	14	1120–2000	21	24–28	37	Cocoa, coffee, rubber, oil palm, ginger
Ultra humid (flood)	2	> 2000	23	25–28	33	
Mountainous	4	1400–2000	5	14–29	32	Cotton, groundnut, tobacco
Plateau	2	1400–1500	14	20–24	36	

Min – minimum; Max – maximum.

energy crop cultivation, and for biofuels production due to the availability of arable lands and water [33,34]. The Food and Agriculture Organization of the United Nations (FAO) estimates in Table 3 shows substantial cultivation of energy crops in Nigeria over a ten-year period.

There have been continuous increases in the areas of land harvested, and tonnes of energy crops produced in Nigeria from 2004 to 2013. Especially with crops such as sugarcane and cassava which are the major feedstocks for emerging biofuel projects in Nigeria (Table 4).

- **Sugarcane**

Ethanol production from sugarcane is currently the most attractive alternative to fossil fuel as it achieves significant GHG emission reductions [2]. It is obtained from renewable biomass: sugarcane and bagasse. Brazil and the United States are the largest producers of ethanol from sugarcane with both countries accounting for about 86% of total bioethanol production in 2010 [2]. In Brazil, the introduction of ethanol in automobiles reduced carbon monoxide emissions from 50 g/km in 1980 to 5.8 g/km in 1995 [14]. The Brazilian economy has grown its sustainable biofuel production from sugarcane as the government-implemented policies have encouraged the production and consumption of ethanol [2].

Sugarcane is grown in several parts of Nigeria, usually on small holdings of 0.2 to 1.0 ha for chewing as juice and as feed for livestock [36]. Following the increase in demand for biofuel production in Nigeria, sugarcane is now grown on a large scale as an industrial raw material. The Nigerian National Petroleum Corporation (NNPC) identifies sugarcane, cassava, sweet potato and maize as the main raw materials for bioethanol production for its Automotive Biofuel Program [26].

Over $3.86 billion has been invested in sugarcane and cassava feedstock plantations in Nigeria, and in the construction of

Table 3
Energy crops cultivation in Nigeria 2004–2013 [35].*Source*: FAO. FAOSTAT. PRODUCTION (Crops). (Latest update: 2013). Accessed 18th January 2016. URL: http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor.

Energy crop	Element	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Sugar cane	Area harvested (Ha)	43,000	44,000	47,000	63,000	71,890	73,060	73,060	74,000	74,000	74,000
	Yield (Hg/Ha)	198,605	207,727	210,000	239,048	196,421	191,853	191,623	195,946	195,946	195,946
	Production (tonnes)	854,000	914,000	987,000	1,506,000	1,412,070	1,401,680	1,400,000	1,450,000	1,450,000	1,450,000
Cassava	Area harvested (Ha)	3,531,000	3,782,000	3,810,000	3,875,000	3,778,000	3,129,030	3,481,900	3,737,090	3,850,000	3,850,000
	Yield (Hg/Ha)	110,011	109,902	120,003	112,026	118,004	117,679	122,155	140,225	140,260	140260
	Production (tonnes)	38,845,000	41,565,000	45,721,000	43,410,000	44,582,000	36,822,250	42,533,180	52,403,455	54,000,000	54,000,000
Sorghum	Area harvested (Ha)	7,031,000	7,284,000	7,308,000	7,812,000	7,617,000	4,736,830	4,960,130	4,891,150	5,500,000	5,500,000
	Yield (Hg/Ha)	12,200	12,600	13,500	11,595	12,233	11,145	14,397	14,101	12,545	12,182
	Production (tonnes)	8,578,000	9,178,000	9,866,000	9,058,000	9,318,000	5,279,170	7140,970	6,897,060	6,900,000	6,700,000
Maize	Area harvested (Ha)	3,479,000	3,589,000	3,905,000	3,944,000	3,845,000	3,350,560	4,149,310	6,008,470	5,200,000	5,200,000
	Yield (Hg/Ha)	16,002	16,598	181,82	17,049	19,571	21,961	18,502	15,279	18,096	20,000
	Production (tonnes)	5,567,000	5,957,000	7,100,000	672,4000	7,525,000	7,358,260	7,676,850	9,180,270	9,410,000	1,0400,000
Oil, palm	Production (tonnes)	1,094,000	1,170,000	1,287,000	1,309,000	1,330,000	1,233,050	970,820	930,000	940,000	960,000
Soybeans	Area harvested (Ha)	587,000	601,000	630,000	638,000	609,000	592,000	281,890	608,650	570,000	600,000
	Yield (Hg/Ha)	8995	9401	9603	9091	9704	7206	10,112	9263	10,175	10,000
	Production (tonnes)	528,000	565,000	605,000	580,000	591,000	426,590	285,050	563,810	580,000	600,000
Millet	Area harvested (Ha)	4620000	4685000	4,971,000	5,056,000	4,904,000	3,787,730	4,364,140	2,889,020	3,800,000	3,800,000
	Yield (Hg/Ha)	14,500	15,300	155,00	16,001	18,483	13,016	11,848	4400	13,158	13,158
	Production (tonnes)	6,699,000	7,168,000	7,705,000	8,090,000	9,064,000	4,929,950	5,170,430	1,271,100	5,000,000	5,000,000
Cocoa, beans	Area harvested (Ha)	1,062,000	1,088,698	1,104,000	1,359,550	1,349,130	1,354,340	1,272,430	1,240,000	1,196,000	
	Yield (Hg/Ha)	3879	4051	4393	2652	2720	2684	3137	3153	3202	
	Production (tonnes)	412,000	441,000	485,000	360,570	367,020	363,510	399,200	391,000	383,000	
Coffee, green	Area harvested (Ha)	3580	3670	3710	2000	2100	1800	2000	2100	2200	
	Yield (Hg/Ha)	13,017	13,597	14,394	12,600	14,286	11,333	12,000	12,381	12,727	
	Production (tonnes)	4660	4990	5340	2520	3000	2040	2400	2600	2800	
Groundnuts, with shell	Area harvested (Ha)	2,097,000	2,187,000	2,224,000	2,202,638	2336,400	2,643,330	2,789,180	2,342,810	2,420,000	2,360,000
	Yield (Hg/Ha)	15,498	15,903	17,199	12,927	12,296	11,265	13,621	12,646	12,690	12,712
	Production (tonnes)	3,250,000	3,478,000	3,825,000	2,847,373	2,872,740	2,977,620	3,799,240	2,962,761	3,071,000	3,000,000
Rice, paddy	Area harvested (Ha)	2,348,000	2,494,000	2,725,000	2451,000	2,382,000	1,836,880	2,432,630	2,579,540	2,685,000	2,600,000
	Yield (Hg/Ha)	14199	14302	14833	12,999	17,544	19,306	18,386	17,706	18,000	18,077
	Production (tonnes)	3334000	3567000	4042000	3,186,000	4,179,000	3,546,250	4,472,520	4567,320	4,833,000	4,700,000
Cotton lint	Production (tonnes)	171,000	190,000	208,000	165,000	180,000	130,000	220,000	103,000	111,500	
Cottonseed	Production (tonnes)	302,000	323,000	350,000	280,000	305,000	225,000	370,000	175,000	189,000	130,000
Taro (cocoyam)	Area harvested (Ha)	640,000	667,000	712,000	739,000	728,000	482,460	520,130	455,301	500,000	500,000
	Yield (Hg/Ha)	74,000	75,982	76,868	67,605	73,997	62,872	56,853	71,727	69,000	69,000
	Production (tonnes)	4,736,000	5,068,000	5,473,000	4,996,000	5,387,000	3,033,340	2,957,090	3,265,740	3,450,000	3,450,000

Table 3 (*continued*)

Energy crop	Element	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Tobacco, unmanufactured	Area harvested (Ha)	25,000	25,000	23,000	19,000	18,000	19,440	18,075	17,925	18,000	
	Yield (Hg/Ha)	6000	6000	6087	4737	6667	7255	9516	9484	9722	
	Production (tonnes)	15,000	15,000	14,000	9000	12,000	14,103	17,200	17,000	17,500	
Wheat	Area harvested (Ha)	58,000	60,000	63,000	26,000	32,000	48,000	66,000	99000	90,000	80,000
	Yield (Hg/Ha)	10,690	11,000	11,270	16,923	16,563	16,667	16,667	16,667	11,111	10,000
	Production (tonnes)	62,000	66,000	71,000	44,000	53,000	80,000	110,000	165,000	100,000	80,000

10,000 units of mini refineries and 19 ethanol bio-refineries, for the annual production of 2.66 billion litres of fuel grade ethanol [18].

- **Cassava**

  Cassava is grown on a commercial scale with Nigeria being the largest producer of cassava in the world [14,34,37]. About 75% of Africa's cassava output is harvested in Nigeria [30]. Agricultural areas harvesting cassava increased from 3,531,000 ha in 2004 to 3,850,000 ha in 2013 with increases in production growing from 38845000 t in 2004 to 54,000,000 t in 2013 (Table 3). Production growth at this rate was the result of a transformation from cassava being firstly a famine reserve crop, then a rural staple food crop, to then a cash crop for urban consumption, and finally to use as an industrial raw material [30]. The International Fund for Agricultural Development (IFAD) and the Food and Agriculture Organization of the United Nations review of cassava in Africa shows how the planting of new varieties of Tropical Manioc Selection (TMS) cassava developed by International Institute of Tropical Agriculture (IITA), and given to Nigerian farmers in the 1970s has transformed cassava from being a low-yielding famine-reserve crop to a high-yielding cash crop.

  Aside from sugarcane, cassava produces the highest amount of carbohydrate. Depending on the cultivar, field management and age, a mature cassava root ranges in length between 0.15 to 1.0 m and weigh 0.5 to 2.5 kg. With time, up to an optimal period of 12 to 15 months after planting, the starch content increases [37]. Cassava requires at least 8 months of warm weather to produce a crop, and may be harvested between 10 to14 months [37]. The Nigerian weather favours its growth especially in the humid tropical zone [29].

  Thus, cassava has high potential as industrial raw material for ethanol production in Nigeria. The process for conversion of cassava for biofuel is already established [18]. However, cassava is considered as a first generation biofuel feedstock in direct competition with food. Despite this, cassava residues (bagasse) which are nonedible can be used for biofuel production. Nigeria has a residue potential of about 7.5 million tonnes/annum [14].

- **Sorghum**

  The use of sorghum as an alternative bioenergy feedstock increased in interest from the 1970s [38]. With the 2008 Farm Bill classification of the sorghum grain as an advanced biofuel feedstock, ethanol production has developed further as a new and important market [38]. Sorghum cultivars are considered as efficient biomass feedstocks for energy conversion because the cultivars possess fermentable sugars that are readily available within the hollow stem of the plant. Hence enzymatic conversion of starch to sugar is not necessary, thus giving sorghum an economic advantage over starch-based crops.

  Nigeria ranks amongst the top four producers of Sorghum in the world: United States 18.68%, Nigeria 17.12%, India 11.27%, and Mexico 9.81% [38]. In 2013, sorghum was harvested on 5,500,000 ha of agricultural land in Nigeria, with aggregate production of 6,700,000 t (Table 3). It is one of the most drought-resistant crops cultivated in the central and western areas in Nigeria [29]. Traditionally, the crop is cultivated for food and beverages and roofing in local communities. However, it is an increasingly attractive feedstock for bioethanol production because of its high sugar content.

  The stalk of sweet sorghum is rich in fermentable sugar which can be extracted as juice [39]. This contains ammonia, acid and minerals enabling it to be used for multiple purposes including fermentation for bioethanol production. Conventional fermentation technology can be used to convert the juice in sorghum into alcohol. The bagasse can be used for co-generation of steam or electricity or as feedstock for cellulosic biofuel production. World Agricultural Supply and Demand Estimate report cited in [38] states that 26% of domestic grain sorghum is utilized in the production of ethanol. Sweet sorghum has the potential to produce up to 1319.82 gallon/ha of ethanol but its use as a feedstock is constrained because of its seasonality.

- **Maize**

  Maize, also referred to as corn, is a major feedstock for the production of liquid biofuel. It accounts for about 8.4% of global ethanol production [40]. In the U.S., it is the major feedstock for the production of ethanol [39,41]. Ethanol obtained from maize accounts for 48 to 59% greenhouse gas emission savings and 1.5 to 1.8 energy balance in the U.S [42]. However, maize has not been favoured as an ethanol feedstock outside of the U.S. because of concerns about competition with food. Ethanol obtained from maize is estimated to reduce greenhouse gas emissions by 40% [43].

  Maize can be cultivated widely though it is grown mainly in temperate climates. Maize has high productivity per unit of land. In the right environments the agricultural output of maize is about 7 to 11 t per ha higher than other cereals; its ethanol yield can amount to 769.89 gallons/ha of corn [41]. However it uses large amounts of fertilizers and pesticides, and thus consumes fossil fuel energy [44]. The conversion process also consumes energy of about 41.60 GJ per ha maize [45]. But water consumption is relatively low [46]: between 3 to 4 L of water per litre of ethanol for feedstock production and in the ethanol conversion process [47].

- **Oil palm**

  Oil palm is a valuable energy crop comprising a kernel (endocarp) enclosed with pulp and mesocarp. The pulp is edible oil, while the kernel oil is used primarily for the production of soap. Both parts can be used in producing biodiesel. Oil palm is the fourth most produced commodity in Nigeria [33]. It is grown predominantly in the south-eastern part of Nigeria on small-scale farming, and as semi-wild palms [41]. Its 2013 production was about 960,000 t (Table 3), and market share 3% [48].

  Oil palm accounts for about 10% of global biodiesel production, and is rapidly increasing particularly in Indonesia and Malaysia [49]. It is the most efficient source for biodiesel yield per unit of

Table 4
Emerging biofuel projects in Nigeria [18].

Project	Cost	Location	Owners	Feedstock	Feedstock quantity (tonnes / year)	Project summary, ethanol production / year	Land take (ha)	Project phase
Automotive biofuel project	$306M	Agasha, Guma, Benue State	NNPC/private sector	Sugarcane	1.8 million	75 million litres, 116,810 metric tonnes (sugar), 59 MW (electricity)	20,000 (16,000 will be cultivated)	Planning
Automotive biofuel project	$306M	Bukaru, Benue State	NNPC/private sector	Sugarcane	1.8 million	75 million litres, 116,810 metric tonnes (sugar), 59 MW (electricity)	20,000 (16,000 will be cultivated)	Planning
Automotive biofuel project	$306M	Kupto, Gombe state	NNPC/private sector	Sugarcane	1.8 million	75 million litres, 116,810 metric tonnes (sugar), 59 MW (electricity)	20,000 (16,000 will be cultivated)	Planning
Automotive biofuel project (Kwali Sugarcane ethanol project)	$80 - 100M	Abuja, FCT	NNPC/private sector	Sugarcane	1.8 million	120 million litres, 10–15 MW (electricity)	26,374 estimated	Planning
Automotive biofuel project	$125M	Ebenebe, Anambra State	NNPC/private sector	Cassava	3–4 million	40–60 million litres	15,000	Planning
Automotive biofuel project	$125M	Okeluse, Ondo State	NNPC/private sector	Cassava	3–4 million	40–60 million litres	15,000	Planning
Ethanol refinery and Sorghum farm	$70M	Arigidi Akoko, Ondo State	Global biofuel Ltd.	Sweet sorghum	1.05 million estimated	84 million litres bio-refineries + farm estimated	30,000 acquired	EPIC
Ethanol refinery and Sorghum farm	$92M	Illemso, Ekiti State	Global biofuel Ltd.	Sweet sorghum	385,000 estimated	30.8 million litres bio-refineries + farm estimated	11,000 acquired	EPIC
Ethanig (via Starcrest Nigeria Energy)	$300M estimated	Kastina Ala/Benue River Basin of Benue State	Private	Sugarcane	3.25 million estimated	100 million litres, sugar, and electricity	50,000	Planning
Ethanig (via Starcrest Nigeria Energy)	$300M estimated	Kebbi State	Private	Sugarcane	3.25 million estimated	100 million litres, sugar, and electricity	50,000	Conception
Savannah sugar company	$167M	Numan, Adamawa State	Dangote Industries Ltd	Sugarcane	1 million	Expansion to produce 100 million litres, 1 billion tonnes sugar, 100,000 metric tonnes fertilizer and 300 MW electricity	36,000 (Lau, Taraba State)	Planning
Kwara Casplex Ltd.	$90M estimated	Kwara State	Private/government	Cassava	300,000 estimated	38.86 million litres	15,000	EPIC
Oke-Ayedun Cassava ethanol project	$18M	Oke-Ayedun, Ekiti State	Ekiti State Government/ Private	Cassava	238,500	38.1 million litres bio-refinery + farm	15,000	EPIC
CrowNet Green Energy ethanol plant	$122M	Iyemero, Ekiti State	Ekiti State Government/ Private	Cassava	150,000	65 million litres, (100 t of starch and 50 t CO_2/ day)	12,500	Operational (4 Sept. 2008)
Cassava ethanol plant	$115M	Taraba State	Taraba State	Cassava	300,000	72 million litres, 360,000 t of cassava flour, 1.87 million tonnes CO_2 and 57 MGy of liquid fertilizer, 1600 MW electricity	30,000	EPIC
Niger State Government ethanol plant	$90M estimated	Niger State	Niger State	Cassava	150,000	27 million litres, bio-refinery + farm estimated	15,000	EPIC
Cassava bioethanol project	$138M	Niger Delta region	NA	Cassava	0.32 million estimated	58 million litres/year bio-refinery + farm	20,000	Conception
Bioethanol from sugarcane/ molasses	$85M	Niger Delta region	NA	Sugarcane	0.857 million estimated	60 million litres	67,692 estimated	Conception
Cassava industrialization project	$16.4M	Ogun State	Private + Government	Cassava	75,000	3 million litres	5000	Conception
National Cassakero cooking fuel programme	$1B	36 states + Abuja	Private	Cassava	8 million	1.44 billion litres	400,000	EPIC

land compared to other oil crops such as soybeans, rapeseed or sunflowers. The average oil yield from oil palm is about 3.74 t/ha/a while for soybean oil it is 0.38, sunflower 0.48, and rapeseed 0.67 [41]. With the increasing demand and high potential for expanded trade opportunities in developing countries, new oil palm plantations for biodiesel production are emerging in Africa and in Latin America [41]. However, Malaysia, Indonesia and Nigeria remain the top three producers of oil palm in the world [33].

- **Soybean**

  Nigeria is ranked 13th largest producer of soybean in the world with average yield of 591,000 metric tonnes [50]. It is estimated that Nigeria had the potential of producing 284.5 ML of biodiesel from 638,000 ha of soybeans cultivated in 2007 (Table 5). Soybean is a major feedstock for biodiesel production in the U.S and in Latin America [41]. China is also a major producer of soybean; however, it does not use it as feedstock for biodiesel production because of its competition with food. Argentina and Brazil are expected to expand to soy oil for biodiesel production due to the availability of land and relatively lower production cost. Though under the current market forces, soybeans tend to be grown as a single crop in these countries, thus posing the challenge of sustainability.

  Research and development into new feedstocks to support future biofuel expansions from versatile crops and non-edible oil seeds such as jatropha is ongoing in Asia and other countries [51]. However, the large gap between future demand and potential domestic supply requires expanding biofuel production in developing countries, which have the land and the climate required for large- scale production of feedstocks.

- **Jatropha**

  Jatropha is a second-generation dedicated energy crop. Its cultivation does not compete with food and other cash crops for arable land as the plant has the ability to survive in marginal lands. Following the rainfall distribution (Table 2), Jatropha can be grown in all ecological zones in Nigeria. Its rainfall requirement is not heavy. The plant can thrive in average annual rainfall of about 250 mm [33]. In Nigeria, Jatropha is yet to be appreciated as a viable economic crop. Its cultivation is still limited to its use as decorative plant or as hedge crops in rural communities. However, various development projects are ongoing across the country for its use as feedstock for biofuel production [50].

  Environmental concerns on the impact of jatropha cultivation on soil quality as well as the effect of caustic effluents from processing of jatropha oil and the toxicity of jatropha seeds, cake, and extracted oil were initially evident. However, these concerns were reduced after it was discovered that jatropha is a viable option for the remediation of metal contaminated soils/land, following the study of Kumar et al. [52] that assessed the remediation potential of jatropha on soils contaminated by petroleum exploitation and spillages from petroleum transportation and products distribution in the Niger Delta region of Nigeria.

  The costs and benefit of investing in biodiesel production from jatropha is worth assessing to ensure the benefits outweigh the economic, social, and environmental cost.

- **Other energy crops**

  Although biofuels can be produced from several other energy crops such as Miscanthus, this paper is focused on those currently in use in Nigeria, so as to align the feedstock availability with the technology readiness level in the country. Central to the selected feedstocks are: the production concentration, input requirements and derivable yield. These vary considerably among crops and locations. Table 5 shows a summary of derivable biofuels from ten different feedstocks: cultivated areas (ha), biofuel type, and estimated biofuel production potential. In terms of biofuel production potential (million litres, ML), the feedstock with the highest yield is palm oil (18,742.5 ML) while coconut has the lowest yield (110.2 ML). Some of the other feedstocks, in order of decreasing biofuel yield are: cassava, groundnut, corn, sugarcane, soybeans, sesame, and cotton seed. This estimate affirms the availability of biomass resources for biofuel production in Nigeria. However, the resources considered in Table 5 are first generation biomass feedstocks in competition with food. Nigeria needs to harness its renewable energy potential from non-food biomass feedstocks for sustainable production of biofuel. Biofuels can positively influence agriculture if non-food feedstocks are utilized. The United States Department of Agriculture estimates that net farm income in the U.S. can increase from 3 to 6 billion US$ annually if switchgrass is used as energy crop [32].

- **Grasses**

  Although biofuels can be produced from several other energy crops such as Miscanthus, this paper is focused on those currently in use in Nigeria, so as to align the feedstock availability with the technology readiness level in the country. Central to the selected feedstocks are: the production concentration, input requirements and derivable yield. These vary considerably among crops and locations. Table 5 shows a summary of derivable biofuels from ten different feedstocks: cultivated areas (ha), biofuel type, and estimated biofuel production potential. In terms of biofuel production potential (million litres, ML), the feedstock with the highest yield is palm oil (18,742.5 ML) while coconut has the lowest yield (110.2 ML). Some of the other feedstocks, in order of decreasing biofuel yield are: cassava, groundnut, corn, sugarcane, soybeans, sesame, and cotton seed. Grasses have high fibre content, and can be converted into biofuel following various biomass conversion techniques including, cellulosic fermentation to ethanol. Most grass species such as *Pennisetum*, *Andropogon*, *Panicum*, *Chloris*, *Hyparrhenia*, *Paspalum* and *Melinis* used as hay and pasture for livestock feed or for soil conservation can serve as energy crops. It is estimated that 200 million tons of dry biomass can be obtained from forage grasses and shrubs [17]. In Nigeria, grassland occupies about 23% of the total land area [53]and is concentrated majorly in the Guinea savannah which is situated in the middle of the country, and extends southwards to southern Nigeria [29]. These grasses are currently underutilised.

Table 5
Biofuel potential production in Nigeria [33].

Derivable feedstock	Cultivated area (ha) 2007	Derivable biofuel type	Estimated Biofuel production potential (million litres, ML)
Sesame	196,000	Biodiesels	136.4
Palm oil	3,150,000	Biodiesels	18742.5
Palm kernel	3,150,000	Biodiesels	18742.5
Ground nut	2,230,000	Biodiesels	2361.6
Soybean	638,000	Biodiesels	284.5
Coconut	41,000	Bioethanol	110.2
Sugarcane	63,000	Bioethanol	378
Cotton seed	434,000	Biodiesels	141.1
Cassava	3,875,000	Bioethanol	15500
Sweet corn	3,944,000	Bioethanol	678.4

2.2. Crop residues

Agricultural residues are organic materials produced as by-product in the course of harvesting and processing agricultural crops. They are classified into two categories [28]: crop residues (materials left or burnt on farms after the harvest of desired crops),

Table 6
Estimated agricultural crop residues for major crops grown in Nigeria [54].

Crop	Product-ion ($\times 10^3$ t)	Residue type	RPR	Moisture Content (%)	Total residue (million tons)	% available	Weight available (million tons)	LHV (MJ/Kg)	Residue energy potential (PJ)
Rice	3368.24	Straw	1.757	12.71	7.86	100	7.86	16.02	125.92
		Husk	0.2	2.37	1.19	100	1.19	19.33	23
Maize	7676.85	Stalk	2	15	15.35	70	10.75	19.66	211.35
		Cob	0.273	7.53	2.1	100	2.1	16.28	34.19
		Husk	0.2	11.11	1.54	60	0.92	15.56	14.32
Cassava	42533.17	Stalks	2	15	85.07	20	17.01	17.5	297.68
		Peelings	3	50	127.6	60	76.56	10.61	812.3
Groundnut	3799.25	Shells	0.477	8.2	1.81	100	1.81	15.66	28.35
		Straw	2.3	15	8.74	50	4.37	17.58	76.83
Soybean	365.06	Straw	2.5	15	0.91	100	0.91	12.38	11.27
		Pods	1	15	0.37	100	0.37	12.38	4.58
Sugarcane	481.51	Bagasse	0.29	50	0.14	80	0.11	18.1	1.99
		Tops/leaves	0.3	10	0.14	100	0.14	15.81	2.21
Cotton	602.44	Stalk	3.743	12	2.25	100	2.25	18.61	41.87
Millet	5170.45	Straw	1.75	15	9.05	80	7.24	12.38	89.63
Sorghum	7140.96	Straw	1.25	15	8.93	80	7.14	12.38	88.39
Cowpea	3368.24	Shell	2.9		9.77	50	4.89	19.44	95.06
Total							**145.62**		**1958.94**

RPR – Residue to product ratio; LHV – lower heating value; PJ – petajoule.

and agricultural industrial by-product (materials produced after crop processing). Crop residues produced during harvest are primary or field-based residues while those produced alongside the product at time of processing are secondary or process-based residues.

Depending on the mode of handling, both field-based and process-based residues have high potential for energy production [48]. Like grasses, they are underused. About 50% of the agricultural residues are burnt on cropland before the start of the next farming season [54]. They are usually used as fodder for livestock, fertilizer for crop regrowth, for soil conservation (i.e. erosion control), or are burnt off.

Agricultural residues vary. Their bulk density, moisture content, particle size and particle distribution are dependent on age of residue, stage of harvest, or physical composition and length of storage and harvesting practices. Table 6 shows estimates of some major crop residues available in Nigeria. These residues have huge energy potential and can contribute greatly to the nation's economy, particularly those from cassava, rice and maize.

The use of non-traditional feedstock such as straws, stalks, and bagasse for biofuel production has the advantage of contributing food into the market, since it is only the crop residues that are used for biofuel production. Irrespective of the process technologies used in bio-refining, intractable waste products that will be difficult to convert into valuable biofuels or biomaterials will be generated. These spent biomass residues may contain lignin fragments, residual carbohydrates, and other organic matter that need to be treated in an environmentally friendly manner, so as to leave little or no ecological footprint. Such wastes and residues are important energy sources in biorefineries given their chemical energy content, and are ideal feedstocks for thermochemical conversion to syngas [55].

2.3. *Forest resources*

Nigeria's land covers range from tropical rain forest in the south to Sahel savannah in the northern part of the country [30]. The rain-forest area generates more woody-biomass than the savannah areas which generates mostly crop residues [54]. About 9.5% of Nigeria's total land area is occupied by forest [56]. But approximately 1200 km^2 of the forest is lost annually [56]. Table 7 shows the extent of Nigeria's forest, and the annual change rate from 1990 to 2000 and from 2000 to 2010.

Table 7
The extent of Nigeria's forest [57].

	unit	Value
Forest area	1000 ha	9041
% of land area	%	10
Area per 1000 people	ha	60
Annual change rate (1990-2000)	1000 ha	−410
	%	−2.7
Annual change rate (2000-2010)	1000 ha	−410
	%	−3.7

Table 8
Inventory from 1998 showing forest plantation distribution across Nigeria [59].

State	Area (ha)	Underbark Volume (m^3)
Lagos	1049	281,869
Ogun	40147	16,830,603
Oyo	6743	2,169,967
Osun	9259	2,625,817
Ondo and Ekiti	23574	8,321,814
Edo	21522	10,609,067
Delta	4014	1,291,681
Rivers and Bayelsa	0	0
Cross Rivers	14364	7,716,584
Akwa-Ibom	2229	659,413
Imo	1252	692,197
Abia	3714	2,007,058
Anambra	3827	1,896,140
Enugu/Ebonyi	13750	7,598,434
Benue	2226	3,023,116
Kwara	9720	4,708,102
Kogi	5503	1,794,826
Niger	5619	2,496,654
Kebbi	891	2,89,821
Kauna	5866	1973,468
Kano	1761	484,782
Plateau/Nasarawa	6938	2,465,098
Adamawa	1249	370,328
Taraba	1394	398,131
Total	**186611**	**80,704,970**
Average (m3/ha)		**432**

Forest is distributed across Nigeria as seen in Table 8. About 95% of these conventional forests in Nigeria are government owned [58]. Unfortunately, these forest areas are not properly

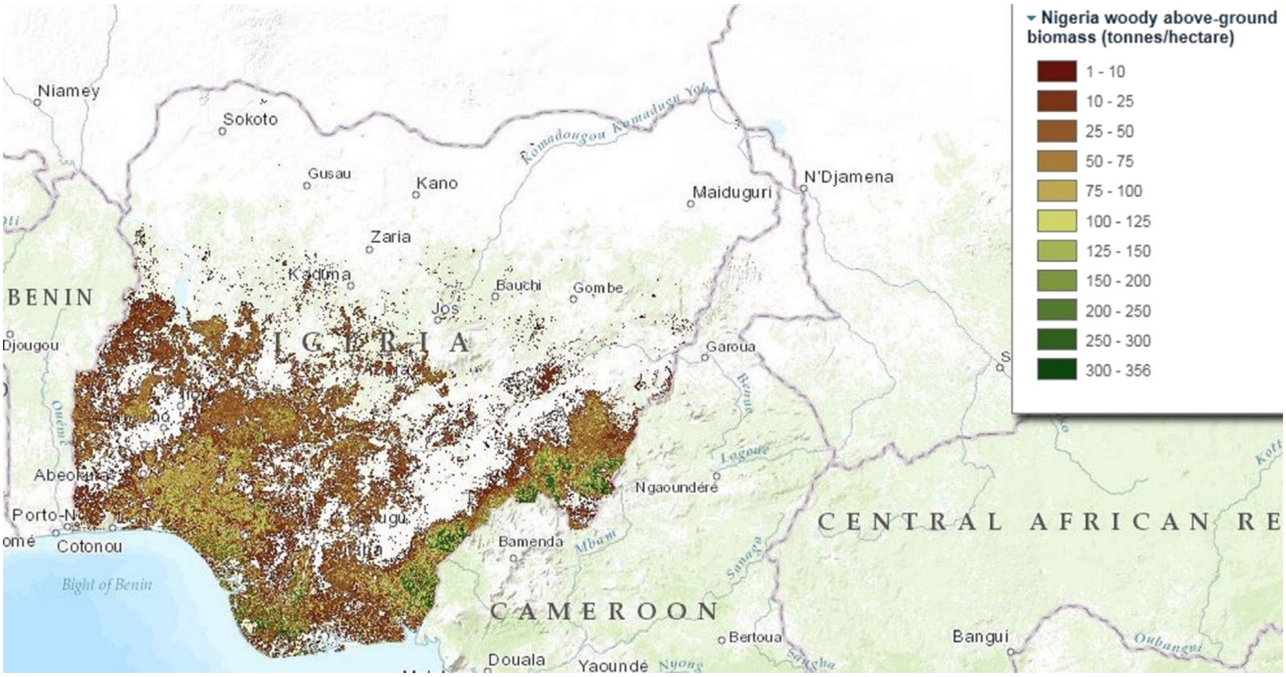

Fig. 5. Nigeria woody above-ground biomass [60].

secured and their resource not conserved. Private individuals easily trespass into the forest and extract its resources for firewood. And so the exact potential of the country's forest biomass is not well known because of poor records of the forest resource production and exploitation.

Forest biomass is categorized into above-ground biomass, and below-ground biomass. Above-ground biomass comprises all living biomass above the soil, which includes barks, branches, foliage, seeds, stems and stumps [59]. The concentration of woody above-ground biomass in Nigeria is shown in Fig. 5. A large amount of this is in the Niger Delta region of the country – the same region that houses most of the existing petroleum refineries. Below-ground biomass is all living biomass of live roots. Sometimes, fine roots of less than 2 mm diameter are not included as they often cannot be empirically differentiated from soil organic matter or litter.

Forest is a major source of biomass that has the potential of contributing substantially to a nation's biofuel resources. Global Forest Resources Assessment (FRA) of Nigeria forest biomass is presented in Table 9.The wealth of forest biomass can be harnessed by utilizing its resources for industrial purposes. Forest-based industries have the opportunity of maximizing renewable energy resources to stir development, create reliable fibre supply, and contribute to domestic economies. For example, forest-based companies are now in the market producing liquid biofuels and other biomaterials through the development of 'bio-refineries' [57].

Many countries are providing support for the development of biofuels and bioenergy, which is somewhat directed towards the forestry sector, as it is believed that the forest industry has a feasible future, particularly with the increasing emphasis on 'green economy'. Canada has paused production at its old pulp and paper mills under its 'Bio-Pathways' project, in order for the country's forest industry to focus on developing the potential of new sawn wood, and other valued wood products to transform its pulp and paper mills into bio-refineries that can produce bioenergy, valuable chemicals and high-performance fibres for advanced applications [57].

Table 9
Biomass stock in forest [59].

FRA 2010 category	Forest Biomass (million metric tonnes oven-dry weight)			
	1990	**2000**	**2005**	**2010**
Above-ground biomass	3,459	2660	2261	1861
Below-ground biomass	830	638	543	447
Total living biomass	4289	3298	2804	2308
Dead wood	601	462	392	323
Total	**4890**	**3760**	**3,196**	**2,631**

Table 10
Production and consumption of forest resources in Nigeria in 2008 [57].

Product	Production (1000 m^3)	Consumption (1000 m^3)	Exports (1000 m^3)
Wood fuel	62,389	62,387	2
Industrial round wood	9418	9379	40
Sawn wood	2000	1994	8
Pulp for paper	23	57	1
Wood based panels	95	161	3
Paper and paper board	19	375	1

Similarly, Nigeria's Biofuel Research Agency is coordinating the biofuel crop production optimization programme in collaboration with Forest Research Institute Nigeria (FRIN) to develop the country's biofuel feedstock. Currently, the largest fuelwood sources are forests, communal farmlands and private farmlands [61]. Wood fuel, including wood for charcoal is a major biomass feedstock used in Nigeria to meet household energy needs. It is the highest produced forest biomass in Nigeria. In 2008, over 62.3 million m^3 wood fuel was produced and consumed (Table 10). It is estimated that about

55% of annual global use of wood is utilized as fuelwood in developing countries [48].

2.3.1. Forest residues

Forest residues are largely untapped biomass energy resources in most parts of Africa [56]. They consist of wood processing co-products such as wood waste and scrap not useable as timber, that is, sawmill rejects, veneer rejects, veneer log cores, edgings, slabs, trimmings, sawdust, and other residues from carpentry and joinery. They also include green waste from biodegradable waste which can be captured and converted into biofuel through gasification or hydrolysis [41].

Like agricultural residues, forest residues are by-products of forest resources. They can be harvested alongside forest resources, and so do not need additional land for cultivation. The availability of forest residues depends on the productivity of the industry where they are obtained. Typical residue yield from a tropical sawmill for export is between 15 and 20% of the total biomass (full tree), or 30–45% of the actual biomass (for example, logs) delivered to the sawmill. These biomass types vary in composition, volume and quality (especially moisture content – from 12% to 55% on a dry basis), depending on the processing steps and soils of origin [54].

2.4. Urban waste and other wastes

The Nigerian environment is highly polluted with enormous amounts of waste: municipal solid waste (MSW), food waste, industrial waste, and animal waste, and these are a major problem in the country. Urban waste and other by-products rich in biomass can be used as feedstocks for biofuel production. The biofuel concept that is capable of producing immediate benefit is biogas from wastes [53]. This does not require irrigation or land input, and could aid reduction in the pervasive use of firewood as well as create a clean environment.

Biogas, a methane-rich gas produced by anaerobic treatment of any biomass, is a multi-benefit, flexible technology that can be applied on household scale, community scale or industrial scale [53]. The technology is straightforward and practicable on both small and large scale. Beside electricity generation, biogas produces fertilizer as a valuable by-product. Biogas can also be upgraded to transportation fuel. However, in Nigeria, the preferred use is as cooking fuel, even though electricity generation would seem an attractive option for large-scale applications considering the poor electricity situation in the country.

The technology to utilize household waste, sewage, industrial waste, and other organic waste can be implemented virtually everywhere in Nigeria. Thus biogas production is an effective way to dispose organic waste, generate energy, produce fertilizer, and circumvent the issue of land and new cultivated areas. A considerable amount of waste is generated in some major cities in Nigeria (Table 11). Maximizing this waste for biogas production, instead of open burning (which is damaging to air quality), could circumvent the tremendous sanitary problem posed in the country.

2.4.1. Municipal solid waste (MSW)

The rate of municipal solid waste generation is highly influenced by population, income level, and activities [48,63]. The type, amount, and concentration of household, commercial, and industrial activities determine the volume of waste generated in a municipality. Table 12 shows total solid waste generated in some major cities in Nigeria.

Municipal solid waste (sometimes called solid waste) is comprised of two main components: biogenic and non-biogenic. The separation of the biogenic component from the non-biogenic components is not efficient in developing countries, especially in the rural areas where there are no proper waste management facilities, so the wastes are burned. In the urban areas, they are basically discarded in dump sites, or used in landfills. Anaerobic digestion of organic waste in landfill releases methane and carbon dioxide into the atmosphere; this pollutes the environment.

Table 11
Waste generation in Nigeria [62].

Regional State capital	Cap/person/day (kg)	Monthly waste (t)	Annual waste (t)	Organic waste (%)	Annual organic (t)
Northeast					
Bauchi	0.31	25,395	304,740	64	195,033.60
Gombe	0.275	14,006	168,072	70	117,650.40
Yola	0.28	25,365	304,380	68	206,978.40
Damaturu	0.242	14,001	168,012	70	117,608.40
Maiduguri	0.28	32,956	395,472	66	261,011.52
Jalingo	0.25	14,253	171,036	70	119,725.20
Northwest					
Kano	0.56	156,676	1,880,112	51	958,857.12
Kaduna	0.23	44,433	533,196	63	335,931.48
Katstina	0.32	18,452	221,424	70	154,996.80
Sokoto	0.281	15,255	183,060	66	120,819.60
Birnin Kebbi	0.28	15,456	185,472	70	129,830.40
Gusau	0.26	14,967	179,604	71	127,518.84
Dutse	0.3	16,340	196,080	70	137,256.00
Northcentral					
Lafia	0.21	13,956	167,472	70	117,230.40
Lokoja	0.26	15,478	185,736	70	130,015.20
Makurdi	0.28	32,956	395,472	66	261,011.52
Ilorin	0.25	34,560	414,720	70	290,304.00
Mina	0.246	14,989	179,868	68	122,310.24
Jos	0.23	27,667	332,004	57	189,242.28
Southeast					
Abakaliki	0.23	14,346	172,152	70	120,506.40
Umuahia	0.23	15,895	190,740	65	123,981.00
Enugu	0.31	16,009	192,108	58	111,422.64
Awka	0.31	25,395	304,740	60	182,844.00
Owerri	0.297	15,846	190,152	70	133,106.40
Southwest					
Lagos	0.73	255,556	3,066,672	36	1,104,001.92
Osogbo	0.24	14,957	179,484	60	107,690.40
Ado Ekiti	0.28	14,784	177,408	65	115,315.20
Ibadan	0.31	135,391	1,624,692	61	991,062.12
Akure	0.32	15,089	181,976	60	108,640.80
Abeokuta	0.36	36,116	1,413,900	60	260,035.20
South–south					
Benin City	0.63	27,459	329,508	54	177,934.32
Yenagoa	0.23	14,246	170,952	65	111,118.80
Calabar	0.26	15,248	182,976	68	124,423.68
Port Harcourt	0.7	117,825	1,413,900	60	848,340.00
Asaba	0.28	15,950	191,400	60	114,840.00
Uyo	0.253	16,112	193,344	58	112,139.52
Other cities					
Aba	0.31	64,347	772,164	70	540,514.80
Onitsha	0.7	84,137	1,009,644	62	625,979.28
Abuja	0.281	14,684	176,208	65	114,535.20

Table 12
Composition of waste in some major cities in Nigeria [63].

City	Putrescible	Plastic	Paper	Textile	Metal	Glass	Others[a]
Nsukka	56	8.4	13.8	3.1	6.8	2.5	9.4
Lagos	56	4	14	–	4	3	19
Makurdi	52	8.2	12	2.5	7.1	3.6	14
Kano	43	4	17	7	5	2	22
Onitsha	31	9.2	23	6.2	6.2	9.2	15.4
Ibadan	76	4	7	1.4	2.5	0.6	8.9
Maiduguri	26	18.1	8	3.9	9.1	4.3	31.3

[a] Others – ash, bones, ceramic, dust, rubber, soil.

The biogenic component can be treated by anaerobic digestion to produce biogas methane. It was estimated that 1 t of MSW deposited in landfill is capable of producing between 160 and 250 m^3 of biogas [62]. The non-biogenic component constitutes the non-biodegradable inorganic substance, such as metal and plastics. Most of the MSW in Nigeria contains biodegradable waste materials because of limited industrial activities in the country.

2.4.2. Food industry waste

Solid and liquid food wastes are generated daily by the food processing industries, hotels and restaurants. These wastes include foods that are not up to the specified quality control standards, peelings and remnants from crops, fruits and vegetables. Hotel and restaurant contributions to the GDP of Nigeria are on the increase. With population of over 170 million, the food industry generates a considerable amount of wastes [54]. Currently, most of these solid wastes end in dumpsites while the wastewater from food industries which usually contains sugars, starch and other dissolved and solid organic matter, constitute environmental pollution.

These food processing wastes which include wastes from dairy and sugar industries, and from wine and beer production, can be anaerobically digested to produce biogas or fermented to produce ethanol [48,54]. The conversion technology depends on the nature and volume of the available waste, and the desired end product. Waste cooking oils can be filtered and used as straight vegetable oil (SVO) or converted to biodiesel [41]. Also, waste streams with smaller volumes (for example orange rind from orange juice production) can also be maximized.

2.4.3. Industrial wastewater/sewage sludge/bio-solids

Large amounts of effluent or wastewater containing organic or inorganic substances are discharged from industries. This may require wastewater treatment depending on the characteristics and amount of wastewater. These industrial wastewater or sewage sludge can be anaerobically digested to produce biogas [54]. However, industrial wastewater treatment in Nigeria is minimal. Most industrial wastewaters are disposed of directly into rivers. Only a few industries carry out primary wastewater treatment by employing either on-site or off-site disposal methods. Nigeria urgently needs to invest in both sewage systems and waste management in order to maximize these resources.

2.4.4. Animal wastes

It is estimated that Nigeria can produce 6.8 million m^3 of biogas daily from fresh animal waste, as 1 kg of fresh animal waste produces approximately 0.03 m^3 gas; and Nigeria generates about 227,500 t of fresh animal wastes per day [53,64]. Animal waste accounts for 61 million tonnes/year of Nigeria's energy reserve [58]. Like agriculture residues, animal wastes are a by-product of livestock rearing. The most common domesticated livestock production in Nigeria comprises cattle, pigs, goats, sheep and chickens (Table 13). The wastes from these animals are one of the most suitable materials for biogas production through the process of anaerobic digestion.

Cattle, goats, and sheep are largely reared in the northern part of Nigeria, while pig cultivation is common in the south. On a typical commercial farm in the north, over one thousand cattle can be found, whereas chicken production predominates in the south. Generally, the majority of urban and rural households in the country keep at least three poultry birds among other ruminant livestock [62]. In terms of biogas production potential from animal waste in Nigeria, the north can be considered more sustainable because of the amount of cattle waste in that region generates.

Urban waste and other waste from non-food crops have high potential for biofuels in Nigeria. They can contribute greatly to supplying a sustainable and clean energy future particularly in the transport sector if technologies to harness these resources are developed.

Table 13
Livestock production in Nigeria 2001–2010 [65].

Year Units	Cattle Head	Pigs Head	Goats Head	Sheep Head	Chickens Head
2004	15,700,000	5,910,000	48,700,000	30,800,000	143,500,000
2005	15,875,300	6,141,220	49,959,000	31,547,900	150,700,000
2006	16,065,800	6,390,000	51,223,600	32,314,200	158,400,000
2007	16,152,700	6,642,340	52,488,200	33,080,300	166,127,000
2008	16,293,200	6,908,030	53,800,400	33,874,300	174,434,000
2009	16,435,000	7,184,360	55,145,400	34,687,300	183,156,000
2010	16,578,000	7,471,730	56,524,100	33,519,800	192,313,000
2011	19,041,270	6,282,453	67,292,536	38,376,024	148,893,000
2012	19,206,928	6,533,751	68,974,848	39,335,424	148,893,000
2013	19,374,029	6,795,101	70,699,218	40,318,809	170,352,000

2.5. Biofuel potential in Nigeria

Following recurrent fuel scarcity issues in Nigeria, and increases in petrol and petroleum prices, Nigeria has started to diversify its fuel supply to use its natural resources more effectively. Biofuel is an attractive alternative to substitute for fossil fuel. Solid biofuels which are used mainly in developing countries, especially wood, account for about 69% of world renewable energy supply, while liquid biofuels account for 4% of transportation supply and 0.5% of global Total Primary Energy Supply (TPES) [66]. Biogas share is about 1.5% and has the highest annual growth rate of 15% since 1990 compared to other biofuels. Liquid biofuels have a significant annual growth rate of 11%, whereas solid biofuels have an annual growth rate of 1% [66].

IEA Statistics reveal that since 1990, bioenergy share has been about 10% of global TPES with an average annual increase of 2% [66]. Bioenergy supply has increased from 38 EJ in 1990 to 52 EJ in 2010 following the rising demand for energy in non-OECD countries and the new policies to increase the share of renewable and domestic energy sources in both OECD non-OECD-countries[66]. Bioenergy is typically the major source of energy in developing non-OECD countries, but covers a minor share of TPES in OECD-countries. China and India were the largest bioenergy producers in 2010, producing 20% and 17%, respectively of the world's bioenergy [66]. China's share of bioenergy was less than 10% of its TPES while India's share was nearly 25%. Nigeria and United States were the third and fourth largest bioenergy producers with shares of over 80% and below 4% respectively [66].

Given that the Clean Development Mechanism (CDM) of the Kyoto Protocol obligates 15 rich countries to invest in green energy in developing countries, the Nigerian National Petroleum Corporation (NNPC) renewable energy program (Automotive Biomass Programme) is likely to attract investment grants. To date, 70,000 Euros grants have been received by NNPC from Germany's Renewable Energy, Energy Efficiency Partnership (REEEP) [67].

The programme is expected to improve the ability of the agricultural sector, create jobs in the rural areas, maximize the country's carbon credits in line with Kyoto protocol of which Nigeria is a signatory [67], and attract grants/funds to the NNPC, while creating opportunity for foreign exchange earnings in the country by exporting surplus products and freezing crude oil in the country that otherwise would be used.

According to the former Group Managing Director of the NNPC, Kupolokun, Nigeria will earn about $150 m annually from the biofuel initiative after take-off [67]. NNPC has an intricate biofuel production program; effort should be directed towards its actualization, rather than on the importing of ethanol. The August 2005 Nigeria Automotive Biomass Programme was established to

Table 14
Biofuel production status in Nigeria [53].

Biofuel	Potential raw material	Industrial feasibility in Nigeria	Proposed use	Main advantage	Land use	Water use
Bioethanol	Sugarcane, sweet sorghum, cassava	Developing	Transportation	Reduced pollution, diversification of fuel mix	Sizeable	Sizeable
Biodiesel	Jatropha, oil palm, soy beans	Under investigation	Transportation	diversification of fuel mix	Depends on crop	Depends on crop
Biogas	MSW, Manure, Sewage	Good	Indoor combustion	Reduced deforestation, improved indoor air quality	None	Limited

develop two major types of biofuels: ethanol from cassava and sugarcane, and diesel from oil palm, as well as integrate the downstream petroleum sector with the agricultural sector.

The renewable energy program is expected to expand the country's energy base and create commercial opportunities for the corporation through partnerships with the private sector, in the form of Joint Ventures (JV's) and agencies with the requisite expertise, such as the various agricultural research institutes in the country. NNPC has MOUs in place with two Brazilian companies, Petrobras and Coimex to leverage on their experience and marketing expertise. Talks with Venezuela's PDVSA were also revived for technology transfer for converting cassava to ethanol [67].

Conversion of starchy feedstocks such as cassava, maize, rice, sweet potato, and yam into bioethanol has been successfully commercialized in several countries. In the U.S., 13.9 billion gallons of bioethanol was produced in 2011 (57.5% of global bioethanol production), almost all of which was from maize [54]. Nigeria's climatic conditions support the production of maize and other starchy feedstocks.

Currently, bioethanol, biodiesel, and biogas are the major biofuels produced in Nigeria (Table 14), of which biogas is more feasible at industrial scale compared to biodiesel which is still under investigation. Biogas also has the advantage of reduced impact on the environment as its feedstock does not pose the threat of deforestation. Ethanol production in Nigeria has been in existence since 1973 with cassava as the main feedstock. One of the major biofuel companies in the country, the Nigeria Yeast and Alcohol Manufacturing Company plans to establish a 200 million USD ethanol plant, with a targeted production of 30 million litres annually [48].

Considering the fact that fossil-based fuel is not keeping pace with the increasing demand for environmentally friendly fuel, it is anticipated that biofuel will significantly impact on the country's petroleum products quality. It has the potential of replacing toxic octane enhancers in gasoline, and thus, reduces particulate emission, tailpipe emissions and ozone pollution. Other anticipated benefits of biofuels are increased economic development, more tax revenue for the government from the industry's economic activities, job opportunities, rural community empowerment, improved farming techniques, increased agricultural research, and increased crop demand [26].

There are several technologies for the conversion of biomass into biofuels, biopower and bioproducts (Figs. 3 and 4). Here, commercially available technologies including those currently in use in Nigeria are included (Table 15). Biomass can be processed through two major conversion pathways: biochemical and thermochemical. The appropriate biomass conversion process is determined by the type and quantity of the biomass feedstock and the desired form of energy (end-use requirements, economic considerations, environmental standards, and product specification) [54].

Furthermore, biomass conversion efficiency is dependent on the feedstock particle size and shape distribution and the type of reactors. A review of some of the conversion technologies is given below.

Table 15
Primary biomass conversion technologies and processed biomolecules [54].

Conversion technology	Fats and oils	Biomass resources		
		Protein	Sugars and starch	Lignocellulose
Direct combustion	√			√
Anaerobic digestion	√	√	√	Cellulose only
Fermentation		√	√	Cellulose only
Vegetable oil transesterification	√			
Pyrolysis	√	√	√	√
Gasification	√	√	√	√

2.6. Biochemical conversion

Biomass composition can be defined from three major components: cellulose, hemicellulose, and lignin. Biochemical conversion processes involve the breakdown of the hemicellulose components of the biomass for the reaction to be more accessible to the cellulose, while the lignin components remain unreacted [54]. Using a thermochemical conversion process, the lignin can be recovered and used as fuel. Biochemical conversion involves two main processes: anaerobic digestion and fermentation.

2.6.1. Anaerobic digestion

Anaerobic digestion is a multi-benefit, flexible technology suitable for energy production from agricultural residues and other biodegradable wastes [53]. It is a feasible option for producing renewable energy for both industrial and domestic use [68]. In anaerobic digestion, high-moisture content (85–90%) biomass is converted by microorganisms in the absence of oxygen to produce a mixture of carbon dioxide (CO_2), methane-rich gas (biogas), and traces of other gases such as hydrogen sulphide [54]. The by-product or nutrient rich digestate from anaerobic digestion can serve as fertilizer for agriculture. Biogas produced from anaerobic digestion has an energy content that is about 20–40% of the lower heating value of the biomass feedstock [54].

In the modern pursuit for clean energy, anaerobic digestion has been investigated for biogas production and for recycling of CO_2 in flue gas [28,68]. Third and fourth generation biomass feedstock, algae, have the capacity to produce methane (biogas) and recycle nutrients by direct use of anaerobic digestion [28]. At present, anaerobic digestion is employed primarily on agricultural residues, animal waste and other wastes in Nigeria for fertilizer and biogas production.

2.6.2. Fermentation

Fermentation is an enzymatic controlled anaerobic process [69]. It is the third step in the production of bioethanol from lignocellulosic biomass. Raw biomass is first pre-treated, then hydrolysed, before fermentation. Pre-treatment increases the surface area of the biomass, decreases the cellulose crystallinity, eliminates the hemicellulose, and breaks the lignin seal. Enzymatic hydrolysis converts the cellulose component of the biomass into glucose, and the hemicellulose component into pentose and hexoses. The glucose is then fermented into ethanol by selected microorganisms.

Fermentation uses microorganisms and/or enzymes for the conversion of fermentable substrates into recoverable products (usually alcohols or organic acids). Currently, ethanol is the most desireable fermentation product, but the production of several other chemical compounds such as hydrogen, methanol, and succinic acid at the moment, is the subject of most research and development programmes. Hexoses, mainly glucose, are the most common fermentation substrates, while pentose (sugars from hemicellulose), glycerol and other hydrocarbons require the development of customized fermentation organisms to enable their conversion to ethanol [70].

Fermentation technology is established and widely used for waste treatment, and for sugar to ethanol production [69]. Brazil developed a successful bioethanol program based on fermentation of sugar in sugarcane feedstock to ethanol. Brazil produced 5.57 billion gallons of ethanol fuel in 2011, accounting for 24.9% of the world's total ethanol used as fuel [54]. Nigeria's climate is similar to that of Brazil and can produce large amounts of sugarcane. The emerging biofuel projects in Nigeria propose sugarcane as feedstock for ethanol production (Table 4).

2.6.3. *Transesterification*

Biodiesel is produced by alcohol transesterification of large branched triglycerides into smaller straight-chain molecules of, for example, methyl esters with enzyme, acid or an alkali as catalyst [53]. The resulting fatty acid methyl esters (FAME) are easily mixed with fossil diesel. Wood extractives consist of vegetable oils and valuable chemicals. The vegetable oil can be converted to biodiesel by transesterification with methanol [69].

Biodiesel technology is still in the emerging phase in Africa; no commercial biodiesel production has been reported [53,71] in spite of feedstock availability and biodiesel potential in Nigeria as shown in Table 5, current biodiesel production exists only at research scale. Trial production of biodiesel from palm kernel oil, and other edible and non-edible feedstocks is also being researched in some Nigerian universities.

2.7. *Thermochemical conversion processes*

Thermochemical conversion processes involves more extreme temperature than that used in biochemical conversion [72]. Examples are: direct combustion, pyrolysis, gasification and liquefaction (Fig. 6).

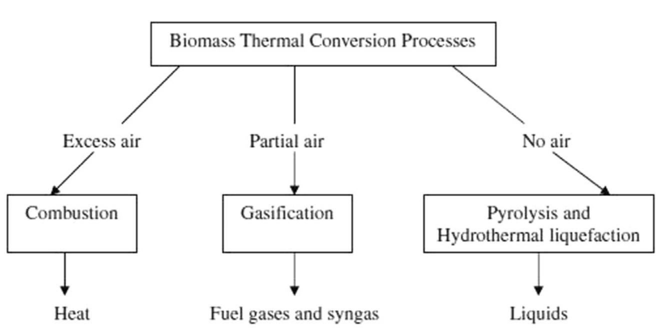

Fig. 6. Thermochemical conversion processes [69].

2.7.1. *Direct combustion*

Direct combustion accounts for over 97% of world bioenergy production [69]. It is the most common way of extracting energy from biomass. Direct combustion can be applied to several fuel materials: energy crops, agriculture residues, forest residues, industrial and other wastes [41]. However, this conversion method is not used for biofuel production [14], as it provides energy only in the form of heat and electric power.

2.7.2. *Pyrolysis*

Pyrolysis is a major biomass conversion process that is precursor to the combustion or gasification of solid fuels. It involves the thermal decomposition of biomass at temperatures of about 350–550 °C, under pressure, in the absence of oxygen [54]. The process produces three fractions: liquid fraction (bio-oil), solid (predominantly ash) and gaseous fractions. Pyrolysis has been applied for thousands of years in charcoal production but is only considered lately because of the moderate temperature and short residence time [73].

The fast pyrolysis process yields liquid of up to 75 wt% which can be used in engines, turbines and refineries or as energy carriers in a variety of applications [73]. Another attraction is the possibility of co-processing fast- pyrolysis oil in a conventional oil refinery, as hydrogen from the refinery can be used to upgrade the oil into transportation fuels, and some off-gases from the pyrolysis plant can be used in the refinery [15,74]. The economics of these options depend on the relative price of natural gas, biomass feedstock and incremental capital costs.

Co-processing of petroleum with renewable feedstock offers advantages from both technological and economical points of view. By using existing infrastructure and configuration, little additional capital investment is required [74]. However the co-location of pyrolysis plant with a refinery also depends on the availability of land, cost of hydrogen and value of the off-gases. The fast pyrolysis of biomass feedstock to bio-crude and subsequent refining to biodiesel and other drop-in fuels is estimated to have the lowest capital cost at about USD 1/litre/year of production capacity for a plant with annual capacity of 289 ML/a [15].

Fully commercialized fast pyrolysis and bio-crude refining to biodiesel and other drop-in fuels can significantly lower costs. If the plant can prove the stability of the process and meet the design availabilities, their biofuels will also be competitive with petroleum products. The first commercial-scale facility using the fast pyrolysis and bio-crude refining process route is the USD 215 million KiOR Inc. plant in Columbus, Mississippi [15]. Currently there are no commercial scale fast pyrolysis plants in Nigeria. Simonyan and Fasina [54] cited two studies on bio-oil production that were carried out in Nigeria using locally cultivated corn cobs. Further research into employing pyrolysis co-processing of bio-oil in the Nigerian refineries is necessary, as the process could reduce the overall capital cost of setting up a stand-alone biorefinery and bring a near-term solution to competitive biofuel production in the country.

2.7.3. *Gasification*

Gasification is the partial oxidation of biomass into a combustible gas mixture at temperatures of 800–900 °C. The gas produced, known as synthesis gas (syngas) consists of a mixture of carbon monoxide (CO – 18 to 20%), hydrogen (H_2 – 18–20%), carbon-dioxide (CO_2 – 8–10%), methane (CH_4 – 2–3%), and traces of other light hydrocarbons (C_5H_{10}), and steam (H_2O) as well as nitrogen (N_2) present in the air that was used for the reaction [54]. The low-calorific value gas produced can be burnt directly or used as a fuel for gas engines and gas turbines in generating electricity. It can also be used as feedstock in the production of chemicals.

Gasification and anaerobic digestion are the two major processes in which biogas can be produced. Based on the available biomass resources in Nigeria (Table 11), biomass gasification can be carried out for biogas production in virtually every state in the country.

2.7.4. Liquefaction

Biomass pyrolysis and direct liquefaction with water are sometimes mixed-up with each other. Both are thermochemical processes where organic compounds in the biomass feedstock are converted into liquid products. In the case of biomass liquefaction, feedstock macro-molecule compounds are decomposed into fragments of light molecules in the presence of a suitable catalyst. At the same time, these fragments, which are unstable and reactive, re-polymerize into oily compounds having appropriate molecular weights. While in pyrolysis, the catalyst is usually not necessary, and the light decomposed fragments are converted to oily compounds through homogeneous reactions in the gas phase [69].

3. Technology readiness level

The technology readiness levels of these biomass conversion processes are at different stages: some are at research and development, others at demonstration stage, and a few are commercially available (Fig. 7).

Conventional biofuels, i.e. biofuel obtained from sugar and starchy crops or by transesterification of vegetable oil, are comparatively mature. However, their feedstocks are first generation biomass, and so face the issue of sustainability. Sustainability of biotechnology can be developed to enhance economic outcomes, increase land-use efficiency and the environmental performance of conventional biofuels. Furthermore, cost improvements can be achieved by co-processing of biofuel and petroleum, that is, by integrating bio-refining with the downstream petroleum processes. Producing conventional and/or advanced biofuels in biorefineries would promote more efficient use of biomass and bring associated cost and environmental benefits.

Generating ethanol from lignocellulosic wastes through hydrolysis and fermentation has the potential to yield an encouraging amount of bioenergy in relation to the required fossil energy inputs, but the technology is yet to be deployed commercially. The conversion of cellulose to ethanol involves two steps: the breakdown of the cellulose and hemicellulose components of the biomass into sugars, and then the fermentation to obtain ethanol. The very wide range of estimated fossil fuel balances for cellulosic feedstocks reflects the uncertainty regarding this technology and the diversity of potential feedstocks and production systems [41].

Africa lacks large oilseed infrastructure (in spite of its agronomical suitability), storing and crushing facilities, as well as operating commercial-scale biodiesel plants. Small to medium, decentralized (localized) biodiesel production with standards satisfactory to engine manufacturers could therefore be a feasible option for boosting development in Africa as it would keep more resources and revenue within communities [71]. An agricultural-based biodiesel model, that is, biodiesel plant located close to an agricultural area with an integrated oil mill is recommended for sustainable production. It will benefit local communities directly.

Such a model increases the scope for regional creation of value and, at the same time introduces biodiesel production in a closed loop recycling management cycle. The biodiesel plant model reduces the feedstock transportation cost due to the close proximity of the feedstock, making it more efficient from energy and cost perspectives.

3.1. Research gaps and way forward

Maximizing biomass resources for commercial production of biofuel in Nigeria is a controversial issue, especially as the emerging biofuels projects in the country propose the utilization of first generation biomass feedstock. Food security could be challenged as high-yielding energy crops such as sugarcane and cassava may be diverted into biofuel production, which could lead to a food crisis. There is need for Nigeria to explore other low-yield biomass feedstocks which are abundant in the country (Tables 6, 10, 11, and 13), such as jatropha for biodiesel production, animal waste or MSW for biogas production.

Biofuel production is still in its early stages of development in Nigeria. Several stakeholders including: the federal government, NNPC, universities, research institutes, private investors, and local farmers have been involved in the Nigerian Automotive Biofuel Programme. The programme which was initiated by the federal

<table>
<tr><th rowspan="2">Bio-product</th><th colspan="5">Advance Biofuels</th><th>Conventional biofuels</th></tr>
<tr><td colspan="2">Basic and applied Research & Development</td><td colspan="2">Demonstration stage</td><td>Early commercial stage</td><td>Commercial stage</td></tr>
<tr><td>Bioethanol (Liquid biofuel)</td><td></td><td colspan="4">Cellulosic ethanol</td><td>Ethanol from sugar and starchy crops</td></tr>
<tr><td>Diesel-type biofuels (Liquid biofuel)</td><td colspan="2">Biodiesel (from microalgae; sugar-based hydrocarbons)</td><td colspan="2">Biomass-to-liquid diesel (from gasification and Fisher-Tropsch Synthesis</td><td>Hydrotreated vegetable oil</td><td>Biodiesel (by transesterification)</td></tr>
<tr><td>Other fuels with additives (Liquid biofuel)</td><td colspan="2">Novel fuels (Example, furans)</td><td colspan="2"></td><td></td><td></td></tr>
<tr><td>Bio-methane (Gaseous biofuel)</td><td colspan="2"></td><td colspan="3">Bio-synthetic gas</td><td>Biogas (anaerobic digestion)</td></tr>
<tr><td>Hydrogen (Gaseous biofuel)</td><td>Other novel routes</td><td colspan="2">Gasification by reforming</td><td>Biogas reforming</td><td></td><td></td></tr>
</table>

Fig. 7. Maturity of different biofuels pathways adapted from IRENA [15].

Table 16
Current ethanol production in Nigeria [18].

Name of company	Plant location	Feedstock	Installed capacity (million L/year)
Alconi/Nosak	Lagos	Crude ethanol (imported)	43.8
UNIKEM	Lagos	Crude ethanol (imported)	65.7
Intercontinental Distillies	Ota-Idiroko	Crude ethanol (imported)	9.1
Dura clean (formerly NIYAMCO)	Bacita	Molasses/ Cassava	4.4
Allied Atlantic Distilleries Ltd. (AADL)	Sango-Ota	Cassava	10.9
Total			**133.9**

government in 2005, gave the NNPC the mandate to carry out 10% blending of biofuel with fossil fuels in the nation's refineries [26].

Currently, there is no commercial biofuel production in Africa [71]. The few ethanol production plants in existence utilize imported crude oil as feedstock (Table 16). Whereas in 2011 the Nigeria Export and Import Bank (NEXIM) granted loans to some companies to commence commercial production of biofuel [75]; most of their projects – both state government and private sector owned – are still in the planning phase (Table 4*)*. Also, the proposed locations for the bio-refineries are far away from the existing petroleum refineries, and would require transportation to the refinery location for blending.

Three out of four of the existing petroleum refineries in Nigeria are located in the Niger Delta region [76]; and this area is characterized by substantial woody above-ground biomass resources (Fig. 5) which can be utilized for biofuel production in the existing refineries. Research [77–79] shows that the production of both gasoline and diesel biofuels employs biomass conversion technologies that produce wide boiling range intermediate oil that requires treatments (such as fluid catalytic cracking, hydrocracking, and hydro-treating) similar to conventional refining. Thus, bio-refineries can leverage on existing petroleum refinery facilities for the finishing of bio-intermediate oils.

Developing biomass conversion facilities in proximity to the existing petroleum refinery infrastructure could reduce the cost of setting up new stand-alone bio-refineries. Nationally, the existing petroleum refineries seem to have adequate processing and hydrotreating facilities to convert bio-derived oils to transportation fuels. However, there are several concerns among which are:

- The low capacity utilization of the existing refineries in the country which is as a result of operational failures, fires and sabotage mainly on the crude pipelines feeding the refineries [80];
- The need to examine the ideal capital investment locations for biomass conversion facilities. For instance, if existing petroleum refining facilities should be expanded to handle a 'raw' bio-oil intermediate, or if it will be best to produce finished biofuels at the new project sites;
- The impact of biomass-derived oil on the existing refinery process, and the ability of the refiners to meet the required product quantity; and
- The need for comprehensive data on the chemical composition of the expected biofuel intermediates, and experience on its behaviour in refining processes (for example, impacts on process performance and reliability).

Addressing these issues requires strong collaboration between the refining industry and the biomass research programmes ongoing in the country. This is in order to identify priorities and opportunities to satisfy knowledge and experience gaps, as well as direct investments to support the Nigerian biofuels objectives. Already, the federal government has put in place some incentives in the Nigerian biofuel policy to promote market entry for investors, and to support biofuel projects in the country, some of which include pioneer status for all registered businesses engaged in biofuel production, waiving the paying of value added tax (VAT), customs duties and the possibility of obtaining long-term preferential loans [26].

The policy seeks to promote investment in Nigeria's biofuel industry by encouraging the participation of all stakeholders. However, on-going debates on the economic opportunities for biofuel production against other environmental and sustainability challenges in the country suggest the industry seems to be taking too long to move out of the planning stage into commercial biofuel production.

3.2. National policy target for biofuels development

Several policy makers view biofuels as a key to reduce dependence on imported oil, decrease greenhouse gas emissions, as well as develop rural areas [81]. Based on current gasoline demand in Nigeria, a policy target of 10% ethanol blending in the nation's refineries has been set [82]. The policy is aimed at integrating the agricultural sector of the nation's economy with the downstream petroleum industry. The target is to achieve 100% domestic biofuels production by 2020. Market demand for gasoline is estimated 1.3 billion litres (Table 17). This is expected to increase to 2 billion litres by 2020. Biodiesel is estimated at 900 million litres by 2020 as compared to current market possibility of about 480 million litres for a 20% blend for biodiesel [82].

The Energy Commission of Nigeria has set up a national energy policy with the objectives as follows [70]:

- **Objectives**

I. To gradually reduce the nation's dependence on fossil fuels while at the same time creating a commercially viable industry that can precipitate sustainable domestic jobs.
II. To gradually reduce environmental pollution.

Table 17
Current ethanol demand in Nigeria [18].

Use	Substitution	Annual consumption (Billion litres)	Government Agency
Transportation	E10 gasoline blend	1.3	NNPC
Household cooking and lighting	Paraffin (replacement with ethanol based cooking gel fuel)	3.75	Nigerian Economic Summit Group
Manufacturing sector	Industrial ethanol demand (wines, chemicals, raw materials, solvents, and pharmaceuticals)	0.09	National Planning Commission
Total		**5.14**	

III. To firmly establish a thriving biofuel industry utilizing agricultural products as a means of improving the quality of automotive fossil-based fuels in Nigeria.
IV. To promote job creation, rural and agricultural development, and technology acquisition and transfer.
V. To provide a framework capable of attracting foreign investment in the biofuels industry.
VI. To streamline the roles of various tiers of government in order to ensure an orderly development of the biofuels industry in Nigeria.
VII. To involve the oil and gas industry in the development of biofuels in Nigeria.

- **Policies** [70]:

I. The nation shall improve on the link between the agricultural sector and the energy sector.
II. The nation shall promote the blending of biofuels as a component of fossil-based fuels in the country as required for all automotive use. The blend shall involve the process of upgrading fossil-based fuels.
III. The nation shall promote investments in the biofuels industry.
IV. The nation shall grant biofuels pioneer status for an initial 10-year period with the possibility of additional 5-year extension.
V. The nation shall support the emergence of an industry in which a substantial portion of feedstock used by biofuel plants will be produced by large – scale producers and out growers.
VI. The nation shall ensure that the biofuel industry benefit from carbon credit.

These policies are in line with the principles cited in [71] (outlined below), in which renewable policy design should reflect. That is

I. The removal of non-economic barriers, such as administrative hurdles, obstacles to grid access, poor electricity market design, lack of information and training, and the tackling of social acceptance issues – with a view to overcoming them – in order to improve market and policy functioning
II. Need for a predictable and transparent support framework to attract investments
III. Introduction of transitional incentives that decrease over time in order to foster and monitor technological innovation and move technologies quickly towards market competitiveness
IV. Development and implementation of appropriate incentives guaranteeing a specific level of support to different technologies based on their degree of technology maturity
V. Consideration of the impact of large-scale penetration of renewable energy technologies on the overall energy system, especially in liberalised energy markets, with regard to overall cost efficiency and system reliability.

To achieve this policy target, short-, medium-, and long-term strategies have been planned [70]:

- **Short-term strategy:**

I. Encouraging integrated (plants and plantations) biofuels operators to set up agricultural service companies to support out-growers scheme.
II. Mandating biofuel producers to establish public private partnership with biofuels feedstock out-growers.
III. Facilitating easy market entry for intending biofuel operators through supportive regulations on biofuel activities.
IV. Granting pioneer status-tax holiday to all registered businesses engaged in biofuels related activities.
V. Granting 10-Year import duty waiver for biofuels equipment not produced locally.
VI. Exempting biofuel companies from taxations, withholding tax and capital gains tax in respect of interest on foreign loans, dividends and services rendered from outside Nigeria to biofuel companies by foreigners.
VII. Granting a single-digit interest on a preferential loan to be made available to investors in the biofuels industry to aid the development of large-scale out-growers schemes and co-located power generating plants.
VIII. Establishing agro-allied industries capable of benefiting from the incentives put in place to foster the development of the agro-allied industry in addition to other incentives.

- **Medium-term** [70]:

I. Reviewing, improving and continuation of short-term strategies.
II. Establishing a research and development fund to encourage synergy between the private and public sectors in R and D in which all biofuel companies shall contribute 0.25% of their revenue for research in feedstock production, local technology development and improved farming practices.
III. Persuading biofuel producers to use auditable feedstock weighing equipment and methodologies as may be prescribed.

- **Long-term** [70]:

I. Reviewing, improving and continuation of medium-term strategies.

However, Ohimain's [82] review of the Nigerian Biofuel Policy and Incentives identified some conflicts, gaps, and inconsistencies in the policy that need to be addressed, particularly, the limiting of biofuels to biodiesel and bioethanol, whereas, there are other energy carries that are obtainable from non-food biomass resources in the country. The policy did not address sustainability issues in terms of the environmental and socio-economic impact, as it is based on the utilization of first generation biomass feedstock for biofuel production. This is not sustainable as it has the potential of igniting a food crisis.

3.3. Sustainability

Globally, countries are imposing blending of transport fuels with 10% biofuels in order to ensure energy security and reduce greenhouse gas emission [40]. An expanding biofuels sector poses both opportunities and threats for sustainable development. The set of opportunities includes increased local use of biomass resources, which may induce rural development and facilitate the production of transportation biofuels, as well as create job opportunities, and improve air quality in cities, while the threats include food crisis, land use change and tenure security, climate change, and socio-economic implications [71].

The continued volatility of fuel prices, the environmental issues associated with GHG emissions, and the combined effect on food and global economics have incited a sense of resolution amongst stakeholders to source for sustainable and viable solutions in the production of biofuels. Sustainable biofuel production involves the utilization of agricultural residues, forest residues, and solid waste. It excludes traditional uses of biomass as fuel-wood. Traditional biomass is not sustainable, and is used in most developing countries as a non-commercial source – usually for cooking. Most Nigerians use traditional biomass such as wood, and charcoal to meet their household energy needs – cooking and heating [13].

Solid waste management in Nigeria is one of the greatest challenges facing state and local government environmental protection agencies [63]. The volume of solid waste generated increases faster than the ability of the waste management agencies to improve on the financial and technical resources needed to parallel this growth. This being stated, it is necessary to consider utilizing these wastes for biogas production for a country with urgent needs for waste management and with ample supply of solid waste across the country (Table 11).

In recent years landfill areas have been a major source of biogas production [53]. Biogas production is a viable option with numerous advantages. Besides being an effective waste management procedure, it is a means of reducing health hazards, indoor air pollution and deforestation. It is flexible in terms of feedstock, does not claim any land, produces fertilizer as a by-product, can be implemented relatively quickly at small scale and is suitable for decentralized use. The technology for biogas production can be implemented almost everywhere with household waste, sewage, industrial waste, agricultural residues and other organic material [53].

Imposing a mandatory 10% blending ratio of biofuels in transportation fuel would, for example, take 85–176 million hectares of arable land, depending on the generation of biofuels – first or second [40]. That is, the crop combination used as feedstock, fraction of residues, and the assumed crop yield. According to [40], these lands engaged for biofuels production could produce food enough to feed 320–460 million people. It is possible that the further use of land for biofuels production could contribute to loss of biodiversity, increase in GHG emissions and trigger food versus fuel competition.

A study carried out by the Centre for International Forestry Research (CIFOR) evaluated the impacts such plantations may have on sustainability and found: biodiversity, soil fertility, and water availability as the major issues with utilizing short-rotation crops for biofuels production. However the impact on biodiversity depends considerably on the land use prior to the change. Though deforestation will normally bring about decrease in biodiversity, the usage of degraded land would improve biodiversity and add to species multiplication. Thus landscape conservation could ensure biofuel sustainability in Africa.

3.3.1. Environmental impact

The growing global demand for clean energy, the concerns about climate change and the need for GHG emissions reduction have challenged most countries to source for alternative forms of energy. Nigeria is not an exception. Environmental sustainability of biofuels is primarily defined in terms of GHG (CO_2, methane, N_2O) emissions reduction, and other emissions resulting from agricultural practices such as the use of fertilizers and pesticides, irrigation, soil tillage, and harvesting [41]. Additionally, land use prior to biofuel conversion is a critical factor in evaluating the environmental impact. GHG reduction potential suffers markedly if grasslands or forests are used for biofuels.

If grasslands or forests are converted into agricultural land to produce biomass, the GHG reduction potential will be different than if biomass production is just started from agricultural land. So far, studies on biomass and GHG emissions assume that land use remains unchanged [41]. Besides GHGs, energy and water resource preservation are other issues to consider when evaluating environmental sustainability. In some circumstances, the quantity of water used and its impact on local water quality and future availability may be the main constraint against biofuels. Linked to water is the problem of fertilizer runoff– especially near streams and rivers.

Nationally, increasing fuelwood consumption contributes to deforestation with consequent desertification and soil erosion [70]. There is concern on the sustainability of sugarcane, in terms of land use change. This has been a particular issue in Brazil, the world's leader in sugar cane ethanol, where sugar cane expansion into grazing areas can push livestock systems into the forest zones. Brazil, being sensitive to these concerns, has placed restrictions on sugar cane expansion areas to minimize the negative impacts [41].

However, oil palm plantations can also pose environmental problems when expansion takes place on sensitive lands (e.g. peat soils, forests). This is a particular concern in Malaysia and Indonesia where some oil palm is planted in drained peat lands, resulting in significant CO_2 emissions outweighing any carbon benefits arising from the new palm-oil plantations [41].

Moreover, expansion of corn for ethanol in the USA – which tends to reduce soybean acreage as corn–soybean rotation contracts – pushes up soybean acreage expansion in Latin America [41]. This, in turn, raises concerns over potential undesirable land expansion and even encroachment into forested areas, with potentially negative environmental and GHG emission consequences.

Consequently, rice husk constitutes one of the major environmental nuisances as it forms the major municipal solid waste heaps in the areas where it is disposed. Most rice husks generated during rice milling are burnt in the field. This kind of traditional disposal method has caused widespread environmental concerns since it causes air pollution. As a result of the health and environmental concerns, many countries have imposed new regulations to restrict field burning activities. Subsequently, methods to dispose and to use agricultural residues such as rice straw and rice husk have shifted towards the global “waste to resource” agenda [18].

3.3.2. Socio-economic implications

As cited in [41] the socio-economic aspect of sustainability can be evaluated in a number of ways: its impacts on employment, wages, health, and gender inclusion. It relies much on the influence of the different stakeholders. Depending on what is being assessed, the location, and the socio-economic implication assessment may cover studies on: the impacts on indigenous peoples, human rights, community health, and physical resettlement.

Usually, biofuels development takes place in rural areas. These areas in Nigeria are characterized by small-scale and subsistence farming. It is believed that biofuels will create jobs and means of livelihood to the rural dwellers by attracting to the agricultural sector, capital investment and new technologies as well as improved access to fertilizers, infrastructure and high yielding varieties. Biofuels production can also increase access to energy services (for example by expanding access to electricity and potable water, reducing workload of women and children who are usually in charge of collecting firewood, and improving health by reducing indoor air pollution). This implies higher rural wages with positive effects for the local economy [41].

When it comes to access to and control of land and other productive assets, in Nigeria, the level of participation in decision-making and socioeconomic activities of the male child is usually more than the female, as it is believed that the female child would eventually marry and leave the family. This is seen in the country's statistics (Table 1). There are more male population economically active in agriculture than female.

Balancing the economic benefits with environmental and social impacts is an important factor. Even when biofuels meet environmental sustainability criteria, they need to also pass economic sustainability standards. That means ensuring production efficiency and profitability requires access to sustainable resources, and reliable output markets. Thus the challenge is achieving all these while ensuring economic viability and minimizing negative environmental and socio-economic impacts [41].

4. Discussion

The sustainable production of transportation fuels from biomass resources in Nigeria requires alternative feedstocks and new technology development. Currently it is not clear that non-food biomass feedstock will be established, as current research provides no evidence for this take up.

The co-processing of bio-intermediate oil with petroleum in conventional refinery infrastructure is dependent on a number of factors, among which are the feedstock type and availability, the energy potential, the capital cost of integrating the biomass pre-conversion facility to the existing conventional refinery infrastructure against the cost of a stand-alone biorefinery, the location of the petroleum refinery and technology transfer.

The transformation of Nigeria to a bio-based economy, where non-food biomass replaces crude oil, will emerge if the identified research gaps, policy shortfall and sustainability issues are addressed. The materializing of the 10% ethanol blending in the nation's refineries to 100% domestic biofuels production in the country by 2020 will be possible if the biomass processing routes and sustainability issues are well defined.

5. Conclusion

This review identifies the biomass resource available in Nigeria and the potential to use these resources to meet the country's biofuel demand. Biomass is obtainable from a wide variety of sources: energy crops, agricultural crop residues, forest resources, urban and other wastes, which are distributed throughout the country based on the climatic and vegetative zones. With rising demands for clean energy and recurrent fuel scarcity, Nigeria needs to diversify its fuel supply and maximize its use of natural resources. Biofuel is an attractive alternative to substitute for fossil fuel.

Nigeria is a net oil importer of transportation fuel. This makes the country vulnerable to volatility in global fuel prices and dependent on foreign exchange to meet its domestic energy needs. The goal therefore is to reduce the high dependence on imported petroleum by maximizing domestic biomass resources for biofuel production. However, this should be achieved sustainably with minimal environmental and socio-economic impact.

With location of the existing petroleum refineries in the Niger Delta region of Nigeria, and the large biomass resources obtainable in the same area, it is pertinent for the Nigerian National Petroleum Corporation to consider as part of its biofuels programme if it is better to produce finished biofuels at the new bio-refineries and transport it to the existing refineries for blending, or if it would be better for existing refining infrastructures in the country to be expanded to process raw biomass into bio-intermediate oil for blending.

References

[1] Andres RJ, Boden TA, Bréon F-M, Ciais P, Davis S, Erickson D, et al. A synthesis of carbon dioxide emissions from fossil-fuel combustion. Biogeosciences 2012;9:1845–71. http://dx.doi.org/10.5194/bg-9-1845-2012.

[2] Cannon JS, Sperling D, editors. Reducing climate impacts in the transportation sector. Dordrecht: Springer Netherlands; 2009http://dx.doi.org/10.1007/978-1-4020-6979-6.

[3] Saboori B, Sapri M, bin Baba M. Economic growth, energy consumption and CO2 emissions in OECD (Organization for Economic Co-operation and Development)'s transport sector: a fully modified bi-directional relationship approach. Energy 2014;66:150–61. http://dx.doi.org/10.1016/j.energy.2013.12.048.

[4] Tajudeen IA. Examining the role of energy efficiency and non-economic factors in energy demand and CO_2 emissions in Nigeria: policy implications. Energy Policy 2015;86:338–50. http://dx.doi.org/10.1016/j.enpol.2015.07.014.

[5] U.S. Energy Information Administration. International Energy Statistics – EIA 2015. ⟨http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=5&pid=5&aid=8&cid=NI,&syid=2004&eyid=2013&unit=MMTCD⟩ [accessed 13.01.16].

[6] Annamalai K. Respiratory quotient (Rq), exhaust gas analyses, CO_2 emission and applications in automobile engineering. Adv Automob Eng 2013;2:2–4.

[7] Howey DD, North DR, Martinez-Botas DR. Road transport technology and climate change mitigation. Grantham Inst Clim Chang 2010.

[8] U.S. Energy Information Administration. How much carbon dioxide is produced by burning gasoline and diesel fuel? – FAQ – U.S. Energy Information Administration (EIA) 2015. ⟨http://www.eia.gov/tools/faqs/faq.cfm?id=307&t=11⟩ [accessed 14.01.16].

[9] Larsen Ulrik, Troels Johansen JS. Ethanol as a fuel for road transportation. 2009.

[10] Balat M, Balat H. Recent trends in global production and utilization of bio-ethanol fuel. Appl Energy 2009;86:2273–82. http://dx.doi.org/10.1016/j.apenergy.2009.03.015.

[11] Melero JA, Iglesias J, Garcia A. Biomass as renewable feedstock in standard refinery units. Feasibility, opportunities and challenges. Energy Environ Sci 2012;5:7393. http://dx.doi.org/10.1039/c2ee21231e.

[12] Demirbas A. Biofuels sources, biofuel policy, biofuel economy and global biofuel projections. Energy Convers Manag 2008;49:2106–16. http://dx.doi.org/10.1016/j.enconman.2008.02.020.

[13] U.S. Energy Information Administration. Nigeria - international energy data and analysis 2015. ⟨http://www.eia.gov/beta/international/analysis.cfm?iso=NGA⟩ [accessed 16.01.16].

[14] Ullah K, Kumar Sharma V, Dhingra S, Braccio G, Ahmad M, Sofia S. Assessing the lignocellulosic biomass resources potential in developing countries: a critical review. Renew Sustain Energy Rev 2015;51:682–98. http://dx.doi.org/10.1016/j.rser.2015.06.044.

[15] IRENA. Road transportation: the cost of renewable solutions; 2013.

[16] Schoene D, Killmann W, von Lüpke H, LoycheWilkie M. Definitional issues related to reducing emissions from deforestation in developing countries. Fao 2007;5:1–26.

[17] Shaaban M, Petinrin JO. Renewable energy potentials in Nigeria: meeting rural energy needs. Renew Sustain Energy Rev 2014;29:72–84. http://dx.doi.org/10.1016/j.rser.2013.08.078.

[18] Ohimain EI. Emerging bio-ethanol projects in Nigeria: their opportunities and challenges. Energy Policy 2010;38:7161–8. http://dx.doi.org/10.1016/j.enpol.2010.07.038.

[19] FAO. FAO Country Profiles. Ctry Profiles - Top Imports United Kingdom 2014. ⟨http://www.fao.org/countryprofiles/index/en/?iso3=NGA⟩ [accessed 17.01.16].

[20] FAO. FAOSTAT 2015. ⟨http://faostat3.fao.org/browse/area/159/E⟩ [accessed 17.01.16].

[21] FAO. Country fact sheet 2016. ⟨http://www.fao.org/nr/water/aquastat/data/cf/readPdf.html?f=NGA-CF_eng.pdf⟩ [accessed 17.01.16].

[22] FAO. AQUASTAT – FAO's information system on water and agriculture. Rome; 2005.

[23] The World Bank Group. Nigeria | Data 2016. ⟨http://data.worldbank.org/country/nigeria⟩ [accessed 17.01.16].

[24] The World Bank Group. Nigeria economic report; 2015.

[25] Edenhofer O, Pichs-Madrga R, Sokona Y, Seyboth K. IPCC special report on renewable energy sources and climate change mitigation summary for policymakers. Intergov Panel Clim Chang 2011:1–24.

[26] NNPC. Official Gazette of the Nigerian bio-fuel policy and incentives. 2007. p. 1–22.

[27] Cherubini F. The biorefinery concept: Using biomass instead of oil for producing energy and chemicals. Energy Convers Manag 2010;51:1412–21. http://dx.doi.org/10.1016/j.enconman.2010.01.015.

[28] Dutta K, Daverey A, Lin JG. Evolution retrospective for alternative fuels: First to fourth generation. Renew Energy 2014;69:114–22. http://dx.doi.org/10.1016/j.renene.2014.02.044.

[29] Aregheore EM. Nigeria: Country pasture/forage resource profile 2005.

[30] FAO, IFAD. A review of cassava in Africa with country case studies on Nigeria, Ghana,the United Republic of Tanzania, Uganda and Benin. Proc. Valid. forum Glob. cassava Dev. Strateg.. Rome: International Fund for Agricultural Development / Food and Agriculture Organization of the United Nations; 2005.

[31] FAO. Countries: Geography - Nigeria 2012. ⟨http://www.fao.org/forestry/country/18310/en/nga/⟩ (accessed 18.01.16).

[32] Huber GW, Iborra S, Corma A. Synthesis of transportation fuels from biomass: chemistry, catalysts, and engineering. Chem Rev 2006;106:4044–98. http://dx.doi.org/10.1021/cr068360d.

[33] Abila N. Biofuels adoption in Nigeria: a preliminary review of feedstock and fuel production potentials. Manag Environ Qual Int J 2010;21:785–95. http://dx.doi.org/10.1108/14777831011077646.

[34] GOPA—International Energy Consultants GmbH. The Nigerian energy sector: an overview with a special emphasis on renewable energy, energy efficiency and rural electrification. Second. Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ) GmbH; 2015.

[35] FAO. FAOSTAT 2014. ⟨http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor⟩ [accessed 18.01.16].
[36] Galadima a, Garba ZN, Ibrahim BM, Almustapha MN, Leke L, Adam IK. Biofuels production in Nigeria: the policy and public opinions. J Sustain Dev 2011;4:22–31. http://dx.doi.org/10.5539/jsd.v4n4p22.
[37] Adeoti O. Water use impact of ethanol at a gasoline substitution ratio of 5% from cassava in Nigeria. Biomass Bioenergy 2010;34:985–92. http://dx.doi.org/10.1016/j.biombioe.2010.02.006.
[38] Shoemaker CE, Bransby DI. Chapter 9 The Role of Sorghum as a Bioenergy Feedstock. Sustain Altern Fuel Feed Oppor Challenges Roadmaps Six US Reg 2010:149–59.
[39] Regassa TH, Wortmann CS. Sweet sorghum as a bioenergy crop: Literature review. Biomass Bioenergy 2014;64:348–55. http://dx.doi.org/10.1016/j.biombioe.2014.03.052.
[40] Bindraban P, Bulte E, Conijn S. Can large-scale biofuels production be sustainable by 2020? Agric Syst 2009;101:197–9. http://dx.doi.org/10.1016/j.agsy.2009.06.005.
[41] Elbehri A, Segerstedt A, Liu P. Biofuels and the sustainability challenge: a global assessment of sustainability issues, trends and policies for biofuels and related feedstocks. 2013.
[42] Liska AJ, Yang HS, Bremer VR, Klopfenstein TJ, Walters DT, Erickson GE, et al. Improvements in life cycle energy efficiency and greenhouse gas emissions of corn-ethanol. J Ind Ecol 2009;13:58–74. http://dx.doi.org/10.1111/j.1530-9290.2008.00105.x.
[43] Hayes DJ. An examination of biorefining processes, catalysts and challenges. Catal Today 2009;145:138–51. http://dx.doi.org/10.1016/j.cattod.2008.04.017.
[44] Bioenergy. a. How much biomass can Europe use without harming the environment? EEA Rep 2006. No 7/2006:67.
[45] Dias De Oliveira ME, Vaughan BE, Rykiel EJ. Ethanol as fuel: energy, carbon dioxide balances, and ecological footprint. Bioscience 2005;55:593. http://dx.doi.org/10.1641/0006-3568(2005)055[0593:EAFECD]2.0.CO;2.
[46] Carpita NC, McCann MC. Maize and sorghum: genetic resources for bioenergy grasses. Trends Plant Sci 2008;13:415–20. http://dx.doi.org/10.1016/j.tplants.2008.06.002.
[47] Aden A. Water usage for current and future ethanol production. Southwest Hydrol 2007;6:22–3.
[48] Duku MH, Gu S, Hagan E Ben. A comprehensive review of biomass resources and biofuels potential in Ghana. Renew Sustain Energy Rev 2011;15:404–15. http://dx.doi.org/10.1016/j.rser.2010.09.033.
[49] Pahl G. Biodiesel: growing a new energy economy. 2nd ed.. Vermont: Chelsea Green Publishing; 2008.
[50] Abila N. Biofuels development and adoption in Nigeria: synthesis of drivers, incentives and enablers. Energy Policy 2012;43:387–95. http://dx.doi.org/10.1016/j.enpol.2012.01.019.
[51] Sarin R, Sharma M, Sinharay S, Malhotra RK. Jatropha-Palm biodiesel blends: an optimum mix for Asia. Fuel 2007;86:1365–71. http://dx.doi.org/10.1016/j.fuel.2006.11.040.
[52] Kumar GP, Yadav SK, Thawale PR, Singh SK, Juwarkar a a. Growth of Jatropha curcas on heavy metal contaminated soil amended with industrial wastes and Azotobacter – a greenhouse study. Bioresour Technol 2008;99:2078–82. http://dx.doi.org/10.1016/j.biortech.2007.03.032.
[53] Ishola MM, Brandberg T, Sanni SA, Taherzadeh MJ. Biofuels in Nigeria: a critical and strategic evaluation. Renew Energy 2013;55:554–60. http://dx.doi.org/10.1016/j.renene.2012.12.021.
[54] Simonyan K, Fasina O. Biomass resources and bioenergy potentials in Nigeria. Afr J Agric 2013;8:4975–89. http://dx.doi.org/10.5897/AJAR2013.6726.
[55] Ragauskas AJ, Williams CK, Davison BH, Britovsek G, Cairney J, Eckert C a, et al. The path forward for biofuels and biomaterials. Science 2006;311:484–9. http://dx.doi.org/10.1126/science.1114736.
[56] Osaghae OJ. Potential biomass based electricity generation in a rural community in Nigeria; 2009.
[57] FAO. State of the world's forests. ⟨http://dx.doi.org/10.1103/PhysRevLett.74.2694⟩; 2011.
[58] Mohammed YS, Mustafa MW, Bashir N, Mokhtar a S. Renewable energy resources for distributed power generation in Nigeria: a review of the potential. Renew Sustain Energy Rev 2013;22:257–68. http://dx.doi.org/10.1016/j.rser.2013.01.020.
[59] FAO. Global forest resources assessment: country report, Nigeria. Rome; 2010.
[60] Baccini A, Laporte N, Goetz SJ, Sun M, Dong H. A first map of tropical Africa's above-ground biomass derived from satellite imagery. Environ Res Lett 2008;3:045011. http://dx.doi.org/10.1088/1748-9326/3/4/045011.
[61] Okorie M. Market/investment case: potential of bio energy/mass in Nigeria: (South East); 2010.
[62] Suberu MY, Bashir N, Mustafa MW. Biogenic waste methane emissions and methane optimization for bioelectricity in Nigeria. Renew Sustain Energy Rev 2013;25:643–54. http://dx.doi.org/10.1016/j.rser.2013.05.017.
[63] Ogwueleka TC. Municipal solid waste characteristics and management in Nigeria. Iran J Environ Health Sci Eng 2009;6:173–80. http://dx.doi.org/10.1016/j.wasman.2007.09.039.
[64] Okeh OC, Onwosi CO, Odibo FJC. Biogas production from rice husks generated from various rice mills in Ebonyi State, Nigeria. Renew Energy 2014;62:204–8. http://dx.doi.org/10.1016/j.renene.2013.07.006.
[65] United Nations F and AO. FAOSTAT; 2015. ⟨http://faostat.fao.org/⟩.
[66] Hänninen R, Hetemäki L, Hurmekoski E. European forest industry and forest bioenergy outlook up to 2050: a synthesis. Finland; 2014.
[67] Nwokeji GU. The Nigerian National Petroleum Corporation and the development of the Nigerian oil and gas industry: history, strategies and current directions. Houston: James A. Baker III Institute for Public Policy Rice University; 2007.
[68] Ward AJ, Lewis DM, Green FB. Anaerobic digestion of algae biomass: a review. Algal Res 2014;5:204–14. http://dx.doi.org/10.1016/j.algal.2014.02.001.
[69] Demirbas A. Biorefineries: current activities and future developments. Energy Convers Manag 2009;50:2782–801. http://dx.doi.org/10.1016/j.enconman.2009.06.035.
[70] ECN. National energy policy [Draft revised edition] 2013.
[71] Amigun B, Musango JK, Stafford W. Biofuels and sustainability in Africa. Renew Sustain Energy Rev 2011;15:1360–72. http://dx.doi.org/10.1016/j.rser.2010.10.015.
[72] Nigam PS, Singh A. Production of liquid biofuels from renewable resources. Prog Energy Combust Sci 2011;37:52–68. http://dx.doi.org/10.1016/j.pecs.2010.01.003.
[73] Bridgwater a V. Review of fast pyrolysis of biomass and product upgrading. Biomass Bioenergy 2012;38:68–94. http://dx.doi.org/10.1016/j.biombioe.2011.01.048.
[74] Al-Sabawi M, Chen J. Hydroprocessing of biomass-derived oils and their blends with petroleum feedstocks: a review. Am Chem Soc 2012;26:5373–99. http://dx.doi.org/10.1021/ef3006417.
[75] Ibrahim A. Assessing the opportunities in the Nigerian biofuel industry; n.d.
[76] NNPC. Refineries & Petrochemicals. Niger Natl Pet Corp 2015. ⟨http://www.nnpcgroup.com/NNPCBusiness/MidstreamVentures/RefineriesPetrochemicals.aspx⟩ [accessed 21.01.16].
[77] Huber GW, Corma A. Synergies between bio- and oil refineries for the production of fuels from biomass. Angew Chemie – Int Ed 2007;46:7184–201. http://dx.doi.org/10.1002/anie.200604504.
[78] Freeman C, Jones S, Padmaperuma A. Initial assessment of US refineries for purposes of potential bio-based oil insertions. 2013.
[79] Maity SK. Opportunities, recent trends, and challenges of integrated biorefinery: Part I. Renew Sustain Energy Rev 2015;43:1427–45. http://dx.doi.org/10.1016/j.rser.2014.11.092.
[80] Ismaila B. A review of performance appraisals of Nigerian Federal Government-Owned Refineries. Energy Power … 2012;4:47–52. http://dx.doi.org/10.4236/epe.2012.41007.
[81] Koh LP, Ghazoul J. Biofuels, biodiversity, and people: understanding the conflicts and finding opportunities. Biol Conserv 2008;141:2450–60. http://dx.doi.org/10.1016/j.biocon.2008.08.005.
[82] Ohimain EI. A review of the Nigerian biofuel policy and incentives (2007). Renew Sustain Energy Rev 2013;22:246–56. http://dx.doi.org/10.1016/j.rser.2013.01.037.

Biomass resources and biofuels potential for the production of transportation fuels in Nigeria

Longhurst, Philip J.

2016-05-26

Ben-Iwo J, Manovic V, Longhurst P. (2016) Biomass resources and biofuels potential for the production of transportation fuels in Nigeria. Renewable and Sustainable Energy Reviews, Volume 63, September 2016, pp. 172-192

http://dx.doi.org/10.1016/j.rser.2016.05.050