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Green fuels: concepts, benefits, and studies in Nigeria

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A survey of the literature is presented on the concept of what green fuels are all about, their classes, showing benefits that could be derivable from different classes of daily waste generated in our communities. Several efforts of researchers, especially Nigerian ones, to ensure government and private investors' attention toward the establishment of functional green fuel refineries, otherwise known as biorefineries, were also reported. Areas lacking significant attention were highlighted, and emphasis was made on the need to give better attention to them in future studies. However, for green fuels to attract the attention of government and private investors, and government to be motivated to adopt the idea of investing in green fuels to promote the efficiency of waste management, it would be essential for the works to consider the exploration of the reaction kinetics and mechanism to facilitate process simulation and pilot plant development studies which would enable the possibility of unravelling the economic potentials of the fuels known for being environmentally friendly and renewable.

Keywords: Green fuels, Biomass wastes, Biofuels, Biorefinery, Renewable fuels.

INTRODUCTION

Fossil fuels are well-known for being a class of material that emerges from the decomposition of carbon-based organisms that have been buried millions of years ago. These buried materials get transformed into coal, gas, and oil deposits known to be non-renewable [1], [2]. Presently, they represent about eighty percent of the globe's energy supply, which finds applications in the production of plastics, pharmaceutical materials, detergents, and other products. Nigeria as a country has been reported to be blessed with coal, oil, and gas of proven deposits of about 639 million tonnes[3], 37-40 billion barrels [4], [5], and 182 trillion cubic feet [6] capacity, respectively. Oil and gas have formed a significant component of Nigeria's revenue generation and a monopoly sector determining the drive of the Nigerian economy ever since the post-independence era [7], [8]. The story of our great country has not been like this before the discovery of the oil deposit, even when coal is still discovered. Agriculture was the driving market before the discovery of crude oil; some of the major cash crops that Nigeria traded in the foreign exchange were cocoa, rubber, palm oil, groundnut, and a lot more. On discovering the oil in Nigeria, attention was shifted from sustaining agriculture as one of the primary drives in our economy to fossil fuels. Instead of seeing fossil fuels as a complementary drive to agriculture, it was taken as a substitute [9]. This movement has made our successful government give better attention to the exploration of crude oil and gas for export purposes even with lesser attention for the local processing of the extracted crude, while the agriculture sector degrades.

Also, the dependency of Nigeria's economy on fossil fuels has fetched the government much revenue, which could have been used to grow other sectors, but the case was different [9]. Not until now has our present government begun to look outside the box of fossil fuels to consider other alternatives like giving attention to taxation and agriculture[10], [11]. Many factors have contributed to this new resolution, some of which were the unpredictable future of fossil fuels, drop-in crude price, the global campaign to discourage the use of fossil fuels, the promotion of green fuels [12], green automobile companies, lesser countries to trade within fossil fuels in future and a lot more [13]–[16].

Fossil fuels have generally contributed to making our environment unsafe through their consistent release of greenhouse gases (GHG), non-biodegradable petroleum products, promotion of global warming, climatic changes like wildfires, and a lot more [17], [18], as shown in Fig 1 [19]. All these unfortunate events reportedly found to be associated with the processing and use of fossil fuels have been a significant driver for the ongoing campaign for the promotion of low-carbon and cleaner energy/fuels [12], [20]–[22]. Having our great nation be left out of the recent ongoing move in most developed nations would cause our economy much challenge to sustain our rising annual budget with the unpredictable fall/rise that fossil fuel would offer in the future. As a result, our nation must

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extend its economic drive and energy mix from petroleum to bio-based fuels, which could be produced from our agricultural materials to boost our agricultural sector and the opportunity of energy to extend our energy mix to the inclusion of green fuels.

Furthermore, our waste management approach is poor and has not gotten the required attention to make our environment friendly and promote good public health in our communities [23], [24]. Dumpsites are sited randomly within the residential places. Wastes are burnt as desired across different dumpsites resulting in the production of several toxic and carcinogenic gases, which would result in serious illnesses [25]–[28]. It is essential to consider the use of the waste-to-wealth approach to consider transforming our waste into green fuels, which has a vast potential of benefits to offer to our communities.

All these concerns have propelled our interest towards the need to preach the epistle of benefits from adopting green fuels through the investment of funds and significant attention into the sector that can improve waste management practice in Nigeria. To unfold these details, the report presents the concept of what the green fuels are all about, their common characteristics, their general classes, materials required for each class of the fuels, and report of studies carried out so far in Nigeria on the subject and future areas that works can pay attention to successfully gain the attention of government and private investors into investing into this noble idea.

CONCEPTS AND BACKGROUND OF GREEN FUELS

According to Finnish Energy Club [29], green fuel can be defined as a type of fuel distilled from plants and animal material, which some believe to be more environmentally friendly than the widely used fossil fuels that power most of the world. It is also known as biofuel, fuel obtained from bio-based sources like animal and plant materials. The desperate search for alternative energy sources gives rise to the green fuel evolving as a possible fuelling option as the world drains its fossil fuel resources. However, according to Finnish Energy Club [29], some detractors suggest that green fuel is a misnomer, as the processing of crops into biofuel creates a considerable amount of pollution that may be just as damaging to the environment current practices. Moreover, Othman *et al.* [30] define the fuel as green hydrocarbons, biofuels produced from biomass sources through various biological and thermochemical processes. It is also regarded as one of the most viable options for reducing CO_2 emissions in the transport sector [31] and as an energy source with the potential to solve a series of problems related to climate and sustainability [32]. Brito *et al.* [33] reported that the supply of these green fuels had claimed 3 % of the energy consumed worldwide in road transportation in 2011. For many years, the United States have been well known as the world's largest biofuel producer, claiming a large percent of the biofuels generated worldwide in 2011, and Brazil is known as the second-largest biofuel producer in the world. The economy of these countries has been promoted mainly through the diversification of the energy mix, which has also aided in extending the drives in their country's economy.

Fig. 1. Vehicles emit smoke on Lagos-Ibadan expressway and Apapa road [19].

COMMON CHARACTERISTICS OF THE GREEN FUELS

These green fuels have many advantageous characteristics that have been making them attractive and have been propelling to campaign for adopting these fuels. Some of the characteristics which have proven the fuel to be a largely suitable one to complement or possibly substitute the current use of fossil fuels are as follows:

Octane rating and greenhouse gas (GHG) emission of the fuels

The high value of octane rating [34] reported for the green fuels has been a significant force propelling the interest of the world towards these fuels over the fossil fuels whose lower octane rating has significantly contributed to some cases of incomplete burning leading to the emission of greenhouse gases (GHG) which have negatively affected the ozone layer of the earth [34], [35]. GHG emission has significantly affected our lives with recent reports on the temperature rise. The higher-octane rating of green fuels could go a long way to address this present challenge thoroughly.

Sustainability and renewability of the fuels

Due to the immense dependency of the green fuels on the biomass and bio-resources for their production, their production has been sustainable, unlike the fossil fuels with a projected timeline in which they are expected to be exhausted [36]. Green fuels have diverse sources from which feedstock could be obtained, including agricultural waste, municipal waste, lignocellulose-based materials, and many other bio-based materials that could go a long way in meeting the green refinery demands. According to Paliwal *et al.* [12], the consumption/ conversion of the environmental wastes in a potential green refinery would further make our environment much more friendly through the reduction of environmental waste deposits randomly littered in the communities, especially in the developing countries.

Heating value of the fuels

According to the literature survey, green fuels had shown a higher oxygen content compared to fossil fuels, and this high oxygen content [37] has resulted in a lower energy content often reported for green fuels like biodiesel [35], bioethanol, and others compared to the fossil fuels [38].

Cetane number of the fuels

This property qualifies the quality of the ignition of the fuel and goes by the European and US-based standards for fuel production. The values reported for the green fuels surpass the required minimum indicating its suitability of substituting and complementing the present use of fossil fuels, with a proven higher cetane value in the literature [34], [35].

CLASSES OF THE GREEN FUELS

In categorizing the green fuels into classes, they can be classified into three primary classes, which are as follows:

First-generation green fuels

This class of biofuels is said to be fuel derived from sources like starch, sugar, animal fats, and vegetable oil in which the oil is sourced *via* the use of conventional production techniques. Examples of some of the most popular types of first-generation biofuels include bioethanol, bio-ethers, biogas, biodiesel, other bio-alcohols, green diesel, biofuel gasoline, syngas, and solid biofuels. Much research works in Nigeria have looked into cassava-to-bioethanol [39], [40], waste food – to – biogas [41], and a lot more.

Second-generation green fuels

These are also known as advanced biofuels derived from different categories of biomass. The biomasses are significant sources from plant materials, as well as from animal materials. This report implies that this class of biofuel does not make use of food or edible materials. The precursors for their production are often referred to as non-food biomass, different from the precursors used in the production of the first-generation biofuels. Examples of this class of biofuels include bio-oil, butanol, cellulosic bioethanol, and mixed alcohols. Works in Nigeria have a look into the bagasse-to-bioethanol [42], [43], cob–to–bioethanol [44], molasses–to–bioethanol [45], [46], yam/cassava/potato peels [40], [42], [47]–[52], fruit peel–to–bioethanol [53], [54], and a lot more.

Third-generation green fuels

They are referred to in the case that the biofuel carbon is derived from aquatic autotrophic organisms like algae. Carbon dioxide, light (photons), and nutrients play essential roles in producing the feedstock or precursor used in the production of this class of biofuels. This report implies that a heterotrophic organism that uses cellulose, hemicellulose, or sugar to produce biofuels is not considered 3G. Biodiesel, bioethanol, and many more biofuels can be produced *via* this pathway. Some of the works done so far in Nigeria include investigating the transformation of algae-to-biodiesel [55], sewage-to-biogas [56] and many others.

GREEN FUELS' BENEFITS TO WASTE MANAGEMENT

Some of the benefits that these classes of green fuels can offer in promoting waste management *via* the use of waste to wealth approach (that is, waste to fuel) are presented as follows:

First-generation green fuels

Our waste foods items from homes, markets, spoiled foods in stores, and the likes that are often thrown into a garbage can be considered for producing 1G-biofuels like bioethanol. Likewise, the used cooking oil can also be transformed into biodiesel [41], [57].

Fig 2. Waste food dumpsite in Port Harcourt, Nigeria [57].

The rising food wastage in Nigeria is significantly becoming a subject of concern irrespective of the rise in the hunger rate reported due to the COVID-19 pandemic and the resulting economic crisis. It was revealed that food worth about 750 billion dollars is wasted annually in Nigeria. Fig. 2 presents a site in Port Harcourt where food wastes are often dumped [58]. This rising food wastage in Nigeria is primarily due to the high cost of storage facilities and the lack of a steady power supply to power the device to preserve their food items at various homes and farm produces after harvest. However, the wasted agricultural produces and foods from various homes can be adequately collected and would be suitable for the production of green fuels like bioethanol, biodiesel, biogas (that is, bio-hydrogen, bio-methane, and many others), and other green chemicals like furan, furfural, hydroxyl methyl furfural, and a lot more.

Second-generation green fuels

Agricultural wastes like leaves, stalks, hulks, cobs, bagasse, and others of similar categories, which are often burnt or used for cooking in our homes, can be used in the production of cellulosic bioethanol, bio-oil, and mixed alcohols [53], [59]–[62]. Fig. 2 presents a case of agricultural wastes like bagasse, stem, leave, straw, and a lot more [62], which are commonly burnt in rural areas and could be converted into green fuels like bioethanol other green chemicals. This approach would help provide a complementary fuel to the present use of fossil fuels, which largely contribute to global warming.

Fig 3. Agricultural wastes like straw leaves and stems from the farm [63].

Fig 4. Open defecation in Bauchi [64].

As the rise in open defecation (as shown in Fig. 3) is becoming a significant subject matter not only in rural areas even in urban communities due to the absence of public toilets within the communities, but many people also refer to the option of defecating in open when they are pressed [64]. Building a public toilet around the community with a central sewage system would offer the best way to address this challenge. The sewage collection base can be used to source the feedstock for biogas like bio-methane, bio-hydrogen, and a lot more, which would go a long way to making our environment much more sustainable and friendly for the residents.

Third-generation green fuels

Cultivating algae for biofuels can be promoted as another aspect of agriculture promotion, which promotes the production of biofuels like biodiesel, which are obtainable from algae and bioethanol using the 3G technology [55], [65].

STUDIES CARRIED OUT SO FAR IN NIGERIA ON THE SUBJECT

Many works in the literature have engaged in the search for ways to advance and actualize green refinery, otherwise known as biorefinery, in Nigeria as a possible substitute or complementary means of relieving the considerable pressure and attention given to the exploration of fossil fuels in our country. Some of the areas that works have been making attempts to address looking into and a brief highlight of their attempts and extents are as follows:

Impact of different enzymes and other factors on the process

Several studies have explored the potential of different enzymes on the different transformation processes involved in producing these fuels, at different stages, some at hydrolysis, and others in digestion processes. At the same time, some considered studying different fermentation processes in search of enzymes that would yield a higher biofuels production. This subject is widely investigated on the production of bioethanol, biogas, and other bio-alcohols and the like fuels in the literature [56], [66]–[71] as shown in Table 1.

The report presented in Table 1 further indicates that some authors focus majorly on the production of green fuels [67], [72], [73] while some others try understanding the use of different feedstock, pretreatment approaches, the initial volume of water, reacting time length, temperature, etc. [69], [74]–[76]. Such studies have enabled to identify favorable conditions for producing various green fuels. Most importantly, ways of transforming our environmental wastes into valuable resources in the form of fuels have been established from their reports.

Table 1. Some experimental (laboratory) studies on green fuel production in Nigeria.

Ref.	Green Fuels	Feed	Study Focus	Findings Made
75	BG	Cassava peel waste & cow dung	Effect of different pretreatment methods, where NaOH, $Ca(OH)_2$ and NH_4Cl were studied	The use of NH_4Cl gives the highest yield of 104,961 cm^3
76	BG	Cow dung	Effect of the initial volume of water and time length	Biogas yield of 23 cm^3
71	BG	Fruit wastes (mango, watermelon, and pawpaw)	Effect of pH, temperature, and anaerobic counts variation over a 45 days retention time	Biogas yield of 4348 cm^3
69	BE	Rice husk	Effect of using different enzymes	*Aspergillus niger* (6.99% yield) and *Trichoderma harzianum* (6.25% yield)
74	BG	Poultry, cow, and kitchen wastes	Effect of using various feeds	Poultry droppings (0.0318 dm^3/day), cow dung (0.0230 dm^3/day), kitchen waste (0.0143 dm^3/day)
73	BD	Neem seed	Effect of variables change on the yield in the presence of CaO/MgO	The highest yield of 96.4% was obtained at 70oC, 60min, 500rpm, 6:1g-methanol-to-oil-ratio, and 1% w/w catalyst.

77	BD	Neem seed	Kinetic studies in the presence of CaO/MgO	The activation energy, Ea, of the reaction to be 406.53 J/mol, while the pre-exponential factor A was found to be 0.01618 1/min (or 0.9 1/h).
54	BE	Pineapple	Optimization studies	Max. bioethanol concentration of 5.82%
78	BD	Non-Edible Indigenous Feedstocks	Optimization studies in the presence of KOH	88.0 % (Rubber seeds), 92.0 % (Avocado Pear seeds) and 96.7% (Nipa Palm Kennel seeds)
79	BD	*Lophira lanceolata* Seed Oil	Optimization studies in the presence of sulphuric acid	Optimum biodiesel yield of 85.0%
80	BD	CaO from animal bone	Optimization studies in the presence of sulfuric acid & economic analysis	87.04% conversion with 3.62 wt% of catalysts
68	BE	Cassava starch hydrolysate	Production of green fuel	92% yield reported
67	BE	Corn stover	Production of green fuel	Bioethanol yield was 143.15mg/L
72	BD	Neem seed	Production studies in the presence of CaO	Biodiesel produced was within range of ASTM standard
77	BD	Neem seed	Production studies in the presence of CaO/MgO	The activation energy, Ea, of the reaction to be 406.53 J/mol, while the pre-exponential factor A was found to be 0.01618 1/min (or 0.9 1/h).
81	BD	Jatropha	Production studies in the presence of NaOH	87% was obtained at 333 Kelvin, oil-to-alcohol molar ratio of 1:6 and 1wt% NaOH catalyst concentration
66	BE	Cassava Starch	Suitability of new strain enzyme as an alternative to the conventional	Bioethanol yield of 5.3% which was found suitable

Note: BE - bioethanol, BG - biogas and BD – biodiesel

Table 2. Some non-experimental (theoretical) studies on green fuel production.

Ref.	Green Fuels	Feed	Study Focus	Findings Made
80	BD	Azadiricha Indica oil & CaO from animal bone	Techno-economic analysis & process modelling	The annual production cost, total capital investment, payback time and internal rate of returns are \$ 3537105, \$ 5243784, 2.67 and 43%, respectively.
82, 83	BE	Sugarcane	Process modelling and pilot plant	A functional pilot was fabricated. And the fuel produced was tested and confirmed to have worked effectively in a portable generating power set.
46	BE	Molasses	Techno-economic analysis & process modelling	The study identified that the project would be economically feasible if the molasses cost is lowered, 20-40% government subsidy or a significant decline in the Dollar/Naira exchange rate.
84–86	BE	Rice husk	Techno-economic analysis & process modelling	Findings from this study indicated that transforming rice husk into bioethanol would not be economically feasible without subsidy
43, 87	BE	Sorghum bagasse	Techno-economic analysis & process modelling	The best return on investment was found to be obtainable at 20 % subsidy (minimum), 0% tax rate (waiver), 150 NGN/\$ (lowest), and 10 NGN/kg (maximum)
88, 89	BE	Sugarcane bagasse	Techno-economic analysis & process modelling	Based on the results obtained, the study shows that the plant would yield a benefit/cost ratio (1.46), net present worth (\$ 4.29 million), payback period (10 yrs) and return on investment (8 %), which suggests that the proposed plant would be economically feasible.

Note: GF – green fuels, BE - bioethanol, BG - biogas and BD - biodiesel

Solid catalyst development

Other works give preferential attention to the study of the exploration of solid catalyst potential in the synthesis of green fuels, green chemicals, and renewable fuel additives like biodiesel, sorbitol, mannitol, 5-hydroxymethylfurfural, carboxylic acids, maleic acid, 2,5-furandicarboxylic acid, and a lot of green products from biomass. Researchers are looking into the possibility of improving yield *via* the identification of suitable solid catalysts with an economic benefit over the age-long use of homogeneous catalysts [72], [77], [81]. Report of works presented in Table 1 showcases some work attempted to synthesize solid catalysts to improve yield and catalyst recovery after being used. Some such works include the report of producing catalysts from animal bone [80]. Another is the blending of CaO with MgO to form a mixed catalyst [73] and many other reports to engineering biodiesel production.

Optimization of the process technology

Some other works explore production parameters involved in the transformation in search of improving the yield *via* advanced optimization approaches like factorial design, response surface methodologies, and many others. Some works (as in Table 1) have employed these methods the search for a way of improving production volume of bioethanol, biodiesel, and other fuels [48], [54], [78], [80], [90]–[93].

Reaction kinetics & molecular modelling

This aspect of study considered the search for insight into the kinetics involved in the reaction process and identification of the reaction mechanism *via* the use of molecular simulation tools to study what happens to the reaction at the molecular-scale level. Only a few works [94]–[97] have given attention to the study of kinetics involved in the process. The bulk of the studies has giving preferential attention to the optimization studies over reaction kinetics. In contrast, no attention is given to computational approaches to explore the kinetics and mechanisms involved in our country's production process, unlike the developed nations' works.

Process simulation and pilot plant development

The absence of vital kinetic data has also contributed to this aspect of study in our country to suffer a lot in terms of promoting the simulation of relevant green fuels production processes due to the significant attention that our experimentalists have been giving to the optimization studies instead of giving preference to reaction kinetics modelling and studies. As a result of these issues of concern, only a few processes have been so far investigated on this subject [43], [89], [98].

Economic and commercialization potentials

The development of technologies without establishing their economic significance remains unattractive to both private and government investors. Despite all the understanding of the facts, only a few works have reported on the economic feasibility of the developed processes in Nigeria, evident with the report presented in Table 2. The bulk of works [43], [46], [99], [100] for bioethanol must have been a contributing factor that began to attract the interest of government investment towards this green fuels as reported in the literature [36] for bioethanol. The literature survey indicated that only the absence of vital information (like reaction kinetics models, which can be used to model processes that could then be used in costing the process) on the other fuels has contributed to the absence of a report on their viabilities.

GOVERNMENT POLICIES FOR GREEN FUELS PROMOTION IN NIGERIA

In promoting the establishment of biorefineries in Nigeria, promoting green fuels affordability and commercialization across the nation, the government develops a structured plan for establishing biorefineries and policies that would attract private entrepreneurs to invest in green fuel productions.

Developmental structure to get green refineries established and green fuel utilization

A survey of the literature [101], [102] indicated that the government of Nigeria had put many measures to promote the adoption of green fuels in the Nigerian States, especially bioethanol fuel, which has recorded significant governmental effort unlike other green fuels like biodiesel, biogas, and many others.

One of the measures deployed by the Nigerian government includes the establishment of a policy to mandate the blending of 10% bioethanol with petrol, otherwise known as gasoline, whose resulting mixture is commonly referred to as E-10 or gasohol. The biofuel program was designed to be in two phases, including "seeding of the market" through the importation of bioethanol to initiate penetration of nation within 3-10 years.

In comparison, the second phase program would entail establishing agricultural plantations and building green refineries where the bioethanol would be produced locally to substitute the imported one since phase one. The report indicated that 1.3 billion litres of bioethanol would be required to meet the demand of compliance with the E-10 policy within the country. Similarly, a policy of blending 20% biodiesel with the petro-diesel (B-20 policy) was made. This policy indicated that the biodiesel market demand would be about 900 million litres by 2020 in Nigeria. In summary, the phase is expected to domesticate the production of green fuels *via* the private investors' program. The Biofuels Energy Commission was charged with setting up policies and managing the green fuel's production and distribution across the nation. A Biofuel Research Agency was designed to be built to research the biofuels in Nigeria with the direction of the Biofuel Energy Commission [101], [103].

Attractive government policies for motivating private investors

Most importantly, the government has designed attractive policies to attract private investors to the sector. Some of the policies set include industry incentives, exemption of green fuel industries from taxation, waiver on imports and customs duties for green refineries, waiver on value-added tax on green production and its feedstocks, availability of long-term preferential loans. Insurance shall be provided for strengthening the production of green fuel's feedstock to adequately cover the inherent risks [101], [104]. Although, the bulk of government effort is majorly on the commercialization of bioethanol in Nigeria with less attention to other green fuels. State governments like Kogi [105], Osun [106], and many other states [107], [108] are already investing in the sector.

CONCLUSIONS

This report has successfully presented the concept of what green fuels are all about, their classes, showing benefits that could be derivable from different classes of daily waste generated in our communities. Several efforts of Nigerian researchers to ensure that government and private investors' attention is gained toward the establishment of functional green fuels refineries (otherwise known as biorefineries) were also reported. Areas lacking significant attention were highlighted, and emphasis was made on the need to give better attention to them in future studies.

For the green fuels to attract the attention of government and private investors, and government to be motivated to adopt the idea of investing in green fuel to promote the efficiency of waste management in Nigeria the further research works need to pay significant attention to the following in their respective drive to see green fuel sets established in Nigeria: (1) reaction kinetic studies and molecular simulation; (2) process simulation and pilot plant development; and (3) economic and commercialization potentials.

In addition, there is a need for government and private entrepreneurs to diversify their efforts into investing in other green fuels in Nigeria in terms of the practice of concentrating majorly on bioethanol, whose economic viabilities have mainly been reported in the literature with insignificant reports for the other green fuels. Hence, future research is encouraged to focus on the study of unfolding the economic significance of investing in other green fuels like biodiesel and biogas.

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