

Lignocellulosic Bioethanol in Nigeria: A State-of-the-Art Review of Feedstocks, Conversion Technologies, and Future Prospects

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Abstract

This review focuses on the use of lignocellulose biomass as a non-conventional source for bioethanol and gasohol production. This is because the increasing demand for traditional energy sources has become increasingly apparent in today's energy landscape, marked by a variety of competing energy sources. Within this complex energy environment, gasohol—a mixture of gasoline and bioethanol in varying ratios—has emerged as a viable alternative to the conventional fossil fuels that have long dominated the energy market. The increasing use of edible crops for bioethanol production has inadvertently created competition with the global food supply chain, resulting in rising food prices and shortages. In recent years, bioethanol from agricultural residues like husks, hulls, cobs, straws, and bagasse has been encouraged. These materials, classified as second-generation (2G) biomass resources, show great promise for the biofuel sector. Their lignocellulosic content makes them valuable bio-resources that can serve as a sustainable source for bioethanol production. However, the technical processes involved in converting these lignocellulosic materials into bioethanol have presented several challenges that hinder their commercial viability. These involve the quality of raw materials available for processing, limitations related to

bioethanol yield, and the high costs associated with the production processes required for bioethanol production. Consequently, this review focuses on the bioethanol derived from locally sourced, underutilised agricultural residues, while examining the strategies involved in solving the technical issues. This represents a promising avenue for advancing renewable energy sources and reducing reliance on fossil fuels, which have faced increasing criticism for their environmental impact.

Keywords:

Lignocellulose biomass, Bioethanol, Agricultural Residues, Gasohol, Renewable

1. Introduction

Environmental pollution, unstable crude prices and fossil fuel reduction have led to a market gap between conventional and non-conventional energy sources. These issues have caused a shift in the adoption of renewable energy sources (Rastogi & Shrivastava, 2017). By responding to the ever-changing oil prices, the United States of America and Brazil adopted bioethanol and gasohol to supplement the use of crude oil in their automotive industry. The Region of Africa is not left out in this shift towards renewable sources. Sugar cane was used for

bioethanol production in Ethiopia in the 1950s. However, due to the market dominance by the US and Brazil, coupled with no market for the commodity, expansion was hindered (Miftah & Mutta, 2024).

Bioethanol production in Ethiopia, nonetheless, showed potential when 38.54 million litres of bioethanol were blended with petrol in a 10% ethanol and 90% gasoline ratio to produce E10 in the capital city of Ethiopia. The move to blend caused a huge saving for the nation of USD 30.4 million, which would have been otherwise spent on gasoline importation (Miftah & Mutta, 2024). Despite the promising results, ethanol production from sugar cane in Ethiopia experienced challenges due to its overlap with the beverage industry. Similarly, Kenya ventured into ethanol production in 1977 by establishing its maiden ethanol plant in Kisumu, the capital city. The plant operation was short-lived because of the competition with the ethanol production industry from sugarcane sources (Fekadu & Bekele, 2017). The objective of this review is to explore the potential socio-economic impacts, such as the creation of jobs, progress in rural regions, energy self-sufficiency, and reduced reliance on fossil fuels.

2. Overview of lignocellulose biomass (LCB) as a sustainable feedstock

LCB from agricultural residues, forestry activities, energy crops and municipal wastes are large renewable resources which can be converted to biofuel and valuable bio-products, and their use for energy production does not displace food and the environment is not hampered by the adoption. LCB are composed of lignin, cellulose and hemicellulose (Dhaliwal et al., 2011). Cellulose (glucan) & hemicellulose (xylan) are the primary sources of sugar (Malherbe & Cloete, 2002), with cellulose as the largest organic compound (Malherbe & Cloete, 2002). A polymeric compound, such as lignin, acts as a protective sheath for the cell wall of the plant, and it is a co-product in the bioethanol production process (Cotana et al., 2014). They

have their use in the chemical industry as resins, lignin gels (El Mansouri et al., 2007). Cellulose and hemicellulose, which are convertible to sugars, occur physiochemically and biologically and are then fermented to obtain bioethanol (Yao et al., 2019). Residues such as wheat straw (WS), sugarcane bagasse (SCB), rice husks (RH) all exemplify the concept of second-generation (2G) biomass. Converting LCB involves a challenging process of breaking the cross-linking between cellulose and hemicellulose fibres encased in a lignin matrix. The cross-linking causes an impediment to the effective application of enzymes and microorganisms. Extensive literature has been dedicated to pretreatment strategies that can effectively break the cross-linking and destabilise the lignin matrix (Z. Wu et al., 2022).

3. The Significance of focusing on Nigeria as a case study for ethanol/ gasohol production

Nigeria is a West African nation with a land area of approximately 0.92 million km² and two seasons (wet and dry seasons) (Akpodigaga-a & Odjugo, 2010). Annual precipitation varies from 3800mm along the coast and 650mm in the northeastern region (Annual State of the Climate in Nigeria Report, 2022). The land distribution is majorly 40% arable crop, 1.4% water bodies and grasslands and forest taking the remainder (National Bureau of Statistics [NBS] & Food and Agriculture Organization [FAO], 2025). Nigeria has agricultural resources like sugar cane, cassava, rice, wheat, etc. These crops generate residues needed for bioethanol production. They are available throughout the country, as displayed in Fig.1. Focusing on Nigeria, a case study for bioethanol production assumes a significant level of importance due to the following reasons: the potential for the country to reduce its reliance on fuel importation while concurrently preserving its foreign currency reserve (Adedeji Shittu et al., 2016). Table 1 shows the grain production in Nigeria, testifying to the viability of harnessing these resources for biofuel production.

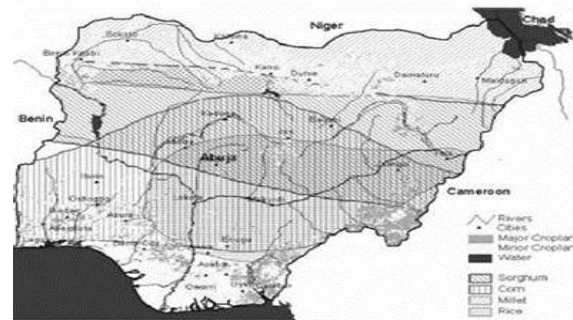


Figure 1. A map showing coarse-grain crop zones in Nigeria (Neszmélyi, 2014).

Table 1. Crop Production in Nigeria covering 2023/2024 market year (Matemilola et al., 2019)

Crops	Year Average (2018-2022) 1000 tons)	2022/2023 (1000 tons)	2023/2024 (1000 tons)
Corn	12283	12735	12000
Sorghum	6589	6742	6700
Rice	5273	5355	5229
Peanut	4321	4294	4300
Millet	1933	2030	2000
Palm Oil	1269	1400	1500
Soybean	1090	1180	1150
Wheat	96	110	120

4.LCB Resources in Nigeria

Municipal solid wastes, forest reserves (FR), and Agricultural residues have been identified as the LCB resources found in the country. These resources can be used for bioenergy applications.(Sambo, 2009). Table 2 highlights

the biomass level and its current utilisation level in the country.

Table 2. Biomass Resources in Nigeria & their estimates 2004 (Sambo, 2009)

Biomass Source	Reserve	Utilisation Level
Fuel wood	11 million hectares of forest and woodlands	43.4 million tonnes of firewood/yr
Municipal waste	18.3 million tonnes in 2005 & about 30 million tonnes/yr now	-
Animal waste	243 million assorted animals in 2001	-
Energy Crops and agric waste	28.2 million hectares of Arable land	8.5% cultivated

4.1 Agricultural Residues from Crop Harvesting Activities

Residues from agriculture are important and can serve as a crucial energy source for domestic and industrial uses. Residues from crop harvest and by-products from agro-industrial processes are the two categories into which agricultural residues are classified. The residues generated after harvest are burned or left on the farmland, causing the emission of particulate matter into the environment. Residues (husks, straws and stalks) are obtained from either crop harvesting activities or agro-processing means. (Aruya et al., 2019). Between 2009 and 2014, about 62 million tons of residues were generated from cassava, plantain, cowpea and groundnut (Jekayinfa & Scholz, 2009). Where a larger quantity of crop residue is required, the crop rotation practice of a higher residue-generating crop can be adopted since residue is directly proportional to crop production. The equation, according to

(Branca et al., 2014), used to express the residue generation and crop production is;

$$Y_{TBE} = Y_{TR} - (Y_{LF} + \sum Y_{OP}) \quad (1)$$

$$Y_{TR} = P_C * RCR \quad (2)$$

Y_{TBE} is the quantity of residue left for bioethanol, Y_{TR} is the total residue produced, Y_{OP} is the quantity of residue that is used for other purposes, P_C is the crop production in (ton/year), and RCR is the residue to crop ratio. Y_{TBE} , Y_{TR} , Y_{LF} , and Y_{OP} are measured in tons/year. Generated residues from agricultural production can decrease petrol consumption by approximately 32% if prioritised. (Metz et al., 2007; Ronzon & Piotrowski, 2017). The assumed RCR for some selected crops can be found in Table 3.

Table 3. Assumed Residue to Crop Ratio (RCR) of some selected crops. (Ullah et al., 2015).

Crop Residue	RCR
Rice Straw	1.5
Rice Husk	0.22
Sugar Cane bagasse	0.33
Maize Straw	1
Coconut shell	0.15
Wheat Straw	1.3
Cotton stalk	1.77
Barley Straw	1.2
Cassava stalk	0.2
Groundnut Straw	2.3
Maize Cob	0.18
Sorghum straw	1.4

4.2. Forest Reserves (FR)

The remnants of various wood processing, such as logging, make up the forest reserve. The logging carried out leaves stalks, stumps, branches and other unused portions of trees. Sawdust from milling activities is an underutilised resource, which constitutes a major concern for millers because it poses an added cost to transportation from the site to disposal sites (Ohunakin, 2010). The wastes from milling activities in this subsector, which entail sawdust, trimming, split wood, and planer shavings, in 2010, were about one million cubic metres (Uche Paul et al., 2018). It is imperative to explore sustainable ways of

harnessing the energy potential that can be derived from these resources.

4.3. Generated Solid Wastes Across Major Cities in Nigeria

Wastes generated in Nigeria amount to about twenty-five million tonnes annually (Ogwueleka, 2009). These wastes take the form of paper, textiles, wood and other organic compounds, thereby presenting a challenging feat to properly dispose of the wastes. Table 4 shows the amount of waste generated by some selected cities in Nigeria. Its generation is dependent on the income levels of the population. Lagos and Kano have the largest

contribution to the waste generation in terms of tonnage. However, Abuja, which has low tonnage, has a higher kg/capita/day. The waste generation rates observed vary between 0.66

kg/capita/day in high-income populations to 0.44 kg/cap/d to low-income populations

Table 4. Waste Generation across Major cities in Nigeria (Ogwueleka, 2009).

City	Population	Tonnage/month	Density(kg/m ³)	kg/capita/day
Lagos	8,029,200	255,556	294	0.63
Kano	3,248,700	156,676	290	0.56
Ibadan	307,840	135,391	330	0.51
Kaduna	1,458,900	114,433	320	0.58
Port Harcourt	1,053,900	117,825	300	0.6
Makurdi	249,000	24,242	340	0.48
Onitsha	509,500	84,137	310	0.53
Nsukka	100,700	12,000	370	0.44
Abuja	159,900	14,785	280	0.6

5. Cellulosic Ethanol Production from Selected Agricultural Crop Residues

5.1 Corn Residues (Zea Mays)

Corn residues such as corn stover (CS), maize straw (MS) and corn cobs have been studied for bioethanol production. (Ado et al., 2009; Ohimor & Eke, 2016). The key findings suggest the possibility of producing bioethanol from them. The pretreatment method applied was a chemical method based on alkaline hydrolysis and acid hydrolysis. The common microorganisms used for fermentation are *Saccharomyces cerevisiae* and *Aspergillus niger* as the microorganisms for fermentation. 16.79mg/g- 17.38mg/g of reducing sugars was produced, suggesting its viability for bioethanol production.

5.2. Rice (Oryza sativa)

This commodity is a staple in many households in Nigeria, cutting across economic classes in Nigeria. Unprocessed rice reached around 8.3 million metric tons in 2021¹. Nigeria contributes 46% of the Western African regional production with an annual consumption valued at four billion US Dollars.²

Shittu et al., (2016) studied the potential of producing bioethanol from rice waste cake using lactic acid bacteria and yeasts in a simultaneous

saccharification and fermentation (SSF) process. The rice cake waste was derived from fermented rice wine mash and composed of 78% carbohydrates and 11% proteins. *Rhodotorula minuta* is the most effective organism, achieving an ethanol efficiency of 52% at optimal conditions. This process demonstrated that a relationship exists between the reduction of reducing sugars and the increase in bioethanol production, establishing the viability of utilising rice waste as a feedstock for bioethanol production.

5.3. Sugar cane (Saccharum officinarum)

The research by (Gani et al., 2018) focuses on the feasibility of using *Saccharomyces cerevisiae* for converting pretreated sugarcane bagasse (SCB) into bioethanol. Their methodology involved a pretreatment with 1% sodium hydroxide followed by a hydrolysis process using dilute sulphuric acid and *Aspergillus niger* to decompose sucrose. The fermentation stage was initiated with *Saccharomyces cerevisiae*, resulting in the highest ethanol yield from a substrate sample (B1) of 0.090%, demonstrating the potential of this yeast in bioethanol production. Building on these findings, (Tope et al., 2023) addressed the economic challenges in bioethanol production from SCB by developing advanced strains of *Saccharomyces cerevisiae* through random mutations. The bagasse underwent a similar hydrolysis process with sodium hydroxide and sulphuric acid, followed by saccharification with *Aspergillus niger*. Local wine sources were utilised to derive *Saccharomyces cerevisiae* for fermentation, and mutant strains were created using various

¹

<https://www.statista.com/statistics/1134510/production-of-milled-rice-in-nigeria/>

The website was assessed on 11-05-2025

² <https://theconversation.com/nigeria-is-africas-leading-rice-producer-but-still-needs-more-reusing-wastewater-for-irrigation-would-boost-farming-206787>. Assessed 11-5-2025

mutagens. Strains SCD and SCK displayed high production levels, having a yield of 9.8 g/ml and 11.2 g/ml of ethanol, respectively, demonstrating improved ethanol tolerance.

The results obtained from the research highlight that there are advancements in bioethanol production from SCB using *Saccharomyces cerevisiae*. The combination of effective pretreatment, hydrolysis, and the development of mutant strains has led to increased ethanol yields, addressing cost-related challenges in production. Identifying the optimal conditions for fermentation further contributes to the efficiency of bioethanol production, showcasing the potential for more sustainable energy solutions.

5.4 Sorghum (*Sorghumbicolor* (L.) Moench)

Sorghum holds the fifth position ranking globally and a second position in Africa, providing sustenance for over five hundred million people indicating its importance in Nigeria. It is cultivated on more than forty-five million hectares and has an annual production surpassing sixty million metric tons (Nasidi et al., 2010). Nigeria is among several countries leading in the harvesting and production of sorghum. It is one of the feedstocks that the Nigerian Government has identified for bioethanol, aiming for self-sufficiency in domestic bioethanol production by 2020, as part of its 2007 Biofuel policy statement (Ishola et al., 2013). Research has demonstrated the potential of sorghum for bioethanol production, particularly through studies by (Nasidi et al., 2013), which focused on two sorghum varieties grown in different climates. By fermenting sorghum stalks under specific conditions, the SSV2 variety showed promising ethanol yields. Following this, another study (Nasidi et al., 2016) explored utilising the entirety of sorghum crop residues, emphasising the importance of both variety selection and environmental factors in optimising ethanol production. The pretreatment process for bagasse included several steps that contributed to the efficiency of bioethanol extraction.

6. Technologies for Processing LCB

6.1 Pretreatment Methods

In extracting bioethanol from LCB, a fundamental process that must be carried out is the pretreatment process. This involves many methods that aim to break the recalcitrance of the structure, enabling the hemicellulose and cellulose structure to be more receptive to further decomposition. The pretreatment method

involves using several techniques, like physical, chemical and biological, which may be applied to the biomass (J. Chen et al., 2024). The various techniques are quite different from one another but may be combined for effectiveness (Meenakshisundaram et al., 2022). The diverse biomass types inform the approach for the desired pretreatment outcomes, and must be cost-effective and efficient (Lynd et al., 1996). Desirable outcomes of the pretreatment methods include enlarged surface area, hemicellulose and lignin removal and a reduction in glucan crystallinity (Mahmoodi et al., 2018). The overall consequences of pretreatment on biomass are manifold and can greatly influence the effectiveness and cost efficiency of the entire production process.

6.1.1. The Physical Method.

The physical method in the pretreatment process may be mechanical, which involves milling or irradiation (Ramanathan et al., 2022). Both of which are meant to achieve a reduced particle size and consequently an increased surface area (Talebna et al., 2010). While size reduction is a desirable outcome for the further process of LCB into bioethanol, tiny particles are not desirable because of the high energy consumption during milling (Talebna et al., 2010). The method centres on disrupting the lignin barrier, thus making reducing sugar available for saccharification (da Silva et al., 2018).

6.1.1.1. Mechanical

The mechanical method is a vital step in the further breakdown of LCB. Size reduction of the LCB is necessary to obtain an increased surface area, as earlier stated. Through milling, either by ball milling or hammer milling, the crystallinity of the raw material is reduced (Carrillo-Nieves et al., 2019). To optimise the size reduction of the lignocellulose biomass, properties such as feed rate, initial particle size, and moisture content of the material are taken into consideration because of the energy-intensive nature of the process (Ra, 2017). However, in deciding which pretreatment to adopt, the efficiency improvement of the method and the cost implications must be seriously considered (Shukla et al., 2023). A desirable outcome from adopting the mechanical process is the non-production of furfurals and hydroxymethylfurfurals, which are both inhibitors. The correlation between the surface area achieved by the mechanical method and

digestibility in the saccharification stage is given by equation (1) (Haghighi Mood et al., 2013).

$$\text{Digestibility} = 2.04(\text{Specific Surface Area})^{0.99} * (100 - \text{CI}) * (\text{Lignin content})^{-0.39} \quad (1)$$

6.1.1.2. Extrusion

This technique combines heat with the physical method, making it a thermo-physical method. It combines low to moderate heating, high shearing of the raw material (LCB) and rapid mixing, leading to significant physical and chemical changes in the compact nature of the biomass (Haghighi Mood et al., 2013). It is a versatile and efficient method used for most applications because it can be operated continuously and handles high loading of the materials with no byproduct (inhibitor) formation (Duque et al., 2017). A desirable quality of using the method is how it enhances the biomass convertibility and the liberation of hexose or pentose sugars, both of which are important to the production of bioethanol (Singh & Trivedi, 2013). Its continuous use makes it desirable to be used extensively; however, its drawback is its energy-intensive nature (Vera-Sorroche et al., 2013). This property can have a negative effect on the overall economics of the use of the method in bioethanol production (Audibert et al., 2025).

6.1.1.3. Sonication

Another method to compromise the rigid structure of the LCB to gain access to cellulose and hemicellulose for enzymatic hydrolysis (EH) is to use ultrasound waves, thereby enhancing the fermentability of fermentable sugars (Das et al., 2021). It can be used alone or combined with other physical methods to improve the economics (Saif Ur Rehman et al., 2013). When ultrasound waves are applied to the biomass, cavitation bubbles are generated, leading to the transformation of the LCB. The factors to consider when using ultrasound wave technology are the duration of the ultrasound waves, the frequency of the ultrasound, temperature and the choice of the aqueous medium (Thakur & Shangvi, 2024). It is an environmentally friendly option which aims to optimise bioethanol yield and minimise the consumption of large amounts of energy in the process (Tang & Sivakumar, 2015). Studies show that ultrasound waves with low frequency are effective for use in processing lignocellulose biomass to bioethanol and other valuable products (Subhedar & Gogate, 2016). The

method has been used on agricultural residues such as sugar cane bagasse (Eblaghi et al., 2016), sweet lime peel (John et al., 2019), and jatropha seed (Shuhairi et al., 2015), and the results show that using the method either as a stand-alone or with another method increased the fermentability of hexose and pentose sugars suggesting access to cellulose and hemicellulose.

6.1.2. Chemical Method

An important method for disrupting the dense structure of lignocellulosic biomass is through the application of chemicals that can decompose the biomass's structure. The chemical pretreatment can be either acid pretreatment, alkaline pretreatment, or organosolv pretreatment (Awogbemi & Kallon, 2022).

6.1.2.1. Alkaline Pretreatment

Alkaline pretreatment entails using bases to solubilise lignin to increase access to cellulose and hemicellulose for fermentation of reducing sugars (Sirohi et al., 2021). The primary target for adopting alkaline pretreatment is to weaken the hold of lignin so that cellulose and hemicellulose can be hydrolysed to fermentable sugars (Ningthoujam et al., 2023). The chemical agents (base) that are often used to weaken and solubilise lignin are sodium hydroxide, calcium hydroxide, and ammonium hydroxide (Sindhu et al., 2015). Alkaline pretreatment can be used in mild conditions of low temperature and pressure, as was the case when (*Arundo donax* L) was pretreated with lye having a concentration of 3.0%. The operating temperature conditions were 60 degrees Celsius and a pretreatment duration of half an hour (Shafaei et al., 2024). The findings indicate that the sodium hydroxide used for alkaline pretreatment is efficient in bioethanol production. Due to its simplicity of use and its non-toxicity, it is less corrosive, with minimal interaction with xylan (Kim et al., 2016). Similar results were obtained when sodium hydroxide was used as the alkaline agent to pretreat *Oryza sativa* husk. The observations from the Fourier Transform Infrared Spectroscopy (FTIR), scanning electron microscopy (SEM) and X-ray Diffraction (XRD) are extensive removal of lignin, distorted surface porosity and structure, and increased crystallite size, respectively (Ningthoujam et al., 2023).

6.1.2.2. Acid Pretreatment.

Mineral acids are also capable of weakening the dense structure of the biomass so that cellulose

and hemicellulose are exposed to enzymatic hydrolysis to produce fermentable sugars (Brodeur et al., 2011). The process may also be referred to as acid hydrolysis. During acid hydrolysis, where the acid acts as a catalyst, the glycosidic bonds in the lignocellulosic structure are severed while attacking the hemicellulosic fraction of the biomass, and solubilising the lignin fraction (Maurya et al., 2015; Sahoo et al., 2018). The products from decomposing hemicellulose during acid hydrolysis are sugars (xylose or mannose) (H. Chen, 2015). The expectation of employing mineral acid as a pretreatment or conditioning agent is the increment in the surface area of the biomass and, lower crystallinity of the biomass. Currently, the most used inorganic acid is tetraoxosulphate (VI) acid because it is cheaper than the present alternatives like hydrochloric acid, nitric acid or phosphoric acid (Agbor et al., 2011; Solarte-Toro et al., 2019). Hsu et al., (2010) expressed the effectiveness of the method as the combined severity factor in equation (2)

$$CSF = \log t + 0.0678(T - T_R) - pH \quad (2)$$

where *CSF* is the combined severity factor, *t* is the reaction time in minutes, *T* is the temperature in degrees Celsius, *T_R* (100⁰C) is the reference temperature in degrees Celsius, *pH* is the initial value of the aqueous solution from the acid concentration, and *A*, *B*, and *C* are coefficients. The drawback of this method is the formation of inhibitors like HMF and furfural, which affect the enzymatic activities and microbial growth for the fermentation of the sugars (McMillan, 1994). The formation of these unwanted and toxic compounds occurs under conditions of high temperatures and high acid concentrations, requiring detoxification to minimise the occurrence of hemicellulose sugar loss (Niju et al., 2020). When acids are used for pretreatment purposes, it is essential to thoughtfully evaluate the need for their recovery and the neutralisation of waste streams to reduce both environmental effects and expenses (Ashokkumar et al., 2022). Studies carried out by (Hsu et al., 2010) and (Avci et al., 2013) on the pretreatment of LCB, such as rice straw and corn stover, establish that lignin's tough structure was disrupted, making a pathway for the liberation of cellulose and hemicellulose for further hydrolysis of sugar into bioethanol.

6.1.2.3. Ionic Liquids (ILs) Pretreatment

ILs are usually composed of large organic cations and small inorganic anions acting as solvents for LCB pretreatment (Olivier-Bourbigou et al., 2010). They can break the extensive hydrogen bonds in the polysaccharides and stimulate their solubilisation. They are characterised by thermal and chemical stability, no flammability, wide liquid temperature ranges and good solvation features for various materials (Hayes et al., 2015). ILs are known as "green" solvents because, during their use, toxic or explosive gases are not formed (Tomas-Pejo et al., 2011). In the process of pretreating switchgrass with ionic liquids (ILs), there was a notable enhancement in the enzymatic saccharification of xylan, resulting in a xylose yield of 63% within 24 hours. Additionally, cellulose exhibited a remarkable glucose yield of 96% over the same time frame.. ILs have been tested to be suitable for use in the pretreatment of LCB, such as bagasse (Dadi et al., 2006), wheat straw (Li et al., 2009). Commonly used solvents for LCB are 1-ethyl-3-methylimidazolium acetate and 1-allyl-3-methylimidazolium chloride (Mäki-Arvela et al., 2010).

6.1.2.4. Organosolv Method Pretreatment

This is another technique employed to decompose lignocellulosic biomass, which consists of plant material, into its fundamental components. This process primarily targets cellulose, hemicellulose, and lignin, utilising organic solvents and water in the presence of a catalyst for effective breakdown (Capolupo & Faraco, 2016). Once the constituents have been fractionated, they can be valorised into other valuable products (Dier et al., 2017). The choice of solvent can depend on various factors like the type of biomass, the desired products, and environmental and cost considerations. Common solvents include ethanol, acetone, and ethylene glycol, among others. The methodology (Anu et al., 2020) has been tested on agricultural residues (Joshi & Adhikari, 2019) and (Mesa et al., 2011), and they have shown remarkable results in the fractionation of the biomass into its constituent compounds.

6.1.3. Physicochemical Pretreatment.

This is an environmentally friendly method which uses steam explosion, ammonia fibre explosion, CO₂, and Liquid Hot Water.

6.1.3.1. Steam Explosion

This physicochemical method for pretreating lignocellulosic biomass (LCB) has been steadily gaining significant attention lately. The technique is notably effective, involving the compression of LCB using steam, followed by a phase of explosive decompression. This procedure consists of two separate stages: vapour cracking and explosive decompression, which lead to alterations in the material's components. These alterations include the hydrolysis of hemicellulose constituents (resulting in the formation of mono and disaccharides), modifications to the chemical structure of lignin, and changes to the cellulose's crystalline index (Keskin et al., 2019). The effectiveness of steam explosion is influenced by particle size, temperature (T), and time (t). The interplay between these factors is expressed as equation (3) (Overend & Chornet, 1987).

$$\log R_o = \log t * \log(e^{(T-100/14.75)})$$

(3)

The steam explosion process presents various appealing advantages when assessed against other pretreatment methods. Notably, it can considerably reduce environmental impact, require less capital investment, enhance energy efficiency, utilise less hazardous chemicals and conditions, and achieve complete sugar recovery (Keskin et al., 2019). Steam explosion technology has been effectively demonstrated as a viable method for producing bioethanol from various biomass sources, including poplar (Oliva et al., 2017), eucalyptus (Ballesteros et al., n.d.), corn stover (Yang et al., 2010), and wheat straw (Ballesteros et al., n.d.). A number of researchers have suggested integrating steam explosion with other pretreatment techniques. For example, options such as alkaline peroxide pretreatment (Tan et al., 2010), ionic liquid (Liu et al., 2012), and superfine grinding pretreatment (Gao et al., 2020) have been developed as promising options for the pretreatment of lignocellulosic biomass (LCB).

6.1.3.2. Ammonia Fibre Explosion (AFEX)

This approach involves treating plant-based biomass by subjecting it to water-free liquid ammonia under high pressure and temperatures ranging from 60°C to 100°C for various periods (Teymouri et al., 2005).

The duration of this treatment is dependent on the temperature; under ambient conditions, it may extend from 10 to 60 days, whereas at elevated temperatures, the effects of ammonia manifest much more rapidly, often reducing the

pretreatment time to just a few minutes, as observed by (Shukla et al., 2023). A significant outcome of treating plant-based biomass with ammonia is the limited decrystallisation of cellulose and the disruption of lignin-carbohydrate bonds (Chundawat et al., 2007), (Teymouri et al., 2005). The AFEX approach is particularly effective for agricultural wastes and herbaceous crops; however, it is less effective for woody biomass and lignin-rich feedstocks (X. Gao et al., 2014). This technique has proven suitable for various materials, including barley straw, corn stover, rice straw (Vlasenko et al., 1997), and bagasse (Blasig et al., 1992). The optimal conditions for using the AFEX method and subsequent saccharification on palm fruit fibre are 135 °C, a residence time of 45 minutes, a water-to-dry biomass ratio of 1:1 (g/g), and an ammonia-to-dry biomass ratio of 1:1 (g/g). These parameters resulted in a 90% mass yield of total reducing sugars after seventy-two hours of enzyme-mediated hydrolysis (Lau et al., 2010). Ammonia usage in pretreatment processes offers numerous advantages, such as its potential for commercial applications, low toxicity levels of the resulting inhibitor, and the elimination of the necessity for water washing, which streamlines the AFEX process (Zhao et al., 2020).

6.1.3.3. Carbon Dioxide (CO₂) Explosion.

The use of supercritical carbon dioxide has been recognised as an effective strategy for speeding up hydrolysis and inducing structural changes in cellulose. This advanced technique has been shown to avoid the formation of harmful chemicals (Agbor et al., 2011b). It involves using supercritical carbon dioxide at specific pressures to improve the digestibility of LCB. Supercritical fluids are substances in a gaseous state compressed to densities comparable to liquids at temperatures above their critical point (Cabeza et al., 2017). The CO₂ explosion pretreatment method is similar to steam explosion, where carbon dioxide is introduced into a high-pressure vessel containing biomass and agitated at around 200°C for a set period. During this process, carbonic acid from the CO₂ penetrates the biomass, aiding in the breakdown of hemicelluloses. Once hemicellulose is degraded, pressure is increased, disrupting the biomass structure and making cellulose more accessible. This environmentally friendly method uses a non-toxic solvent (Ge et al., 2020); water, carbon dioxide, and ammonia are commonly utilised in their supercritical states (Williams et al., 2002).

Supercritical CO₂ is mainly used as an extraction solvent because of its non-toxic, non-flammable, cost-effective, and readily available properties, while also preventing the formation of inhibitory substances (Arumugham et al., 2021). The occurrence of a supercritical CO₂ explosion involves the sudden release of pressure, leading to the disintegration of cellulose and hemicellulose fractions, thereby increasing the surface area available for enzyme activity (M. Gao et al., 2010). Among its many advantages are cost-effectiveness, absence of harmful by-products, lower operating temperatures, and improved solids management capabilities (Alinia et al., 2010).

6.1.3.4. Liquid hot water Method (LHW)

Alternative terms for this approach include hydro-thermolysis, aquasolv steam, or liquid fractionation. The process involves using heated water that has been pressurised to about 5 MPa and operated within a temperature range of 170–230 °C for a few minutes before being depressurised to atmospheric pressure. The hot water maintains the LCBs in a liquid state to prevent deterioration within 160 °C to 250 °C, with a steady heating rate of 20 °C per minute and a residence time between 5 and 20 minutes. During this process, lignin is removed, hemicellulose is broken down, and cellulose becomes more accessible. Hydrothermal pretreatment has been performed using various reactor designs, such as co-current, counter-current, and flow-through configurations, depending on how water and biomass flow within the reactor. The interaction occurs around 200 to 230 °C temperature for about 15 minutes. The hot water disrupts hemiacetal linkages and releases acids during biomass hydrolysis, helping to cleave ether linkages in the biomass. (Mosier et al., 2005) applied this technique to corn fibre slurry in a reactor operating at 163 L/min with a residence time of 20 minutes. This study demonstrated that it is feasible to scale up hydrothermal pretreatment for processing large quantities of corn fibre.

Furthermore, the pretreatment has shown compatibility with other pretreatment techniques such as biological pretreatment (Wang et al., 2012), chemical pretreatment (Zhuang et al., 2016), and physicochemical methods (Imman et al., 2018). In essence, hydrothermal pretreatments provide cost benefits as they eliminate the need for catalyst and allow for the development of economical reactors due to low

corrosion susceptibility. Another key advantage is the lower concentrations of solubilised hemicellulose and lignin products achieved, owing to higher water input, which subsequently leads to a reduction in degradation by-products. Compared to steam explosion, higher recovery of pentosans and lower formation of inhibitors can be attained; however, the process is water-intensive and requires more energy, which impedes its commercial development.

6.1.4. Biological Method of Pretreatment

Biological pretreatment involves using microbes such as bacteria or fungi to break down the complex structure of plant-based biomass. This process converts biomass into simpler, more digestible components, including sugars, which can then be valorised into valuable products (Kuhad et al., 2024). Bacteria and fungi, especially white-rot fungi, produce enzymes (cellulases, xylanases, and ligninases) capable of degrading the main components of biomass (lignin, cellulose, and hemicellulose) (Neshat et al., 2017). *Ceriporiopsis subvermispora* (*C. subvermispora*), a white-rot fungus, demonstrates high lignin selectivity, an accelerated degradation rate, and minimal cellulose loss (Wan & Li, 2012). Due to the lengthy duration of biological pretreatment, it is often combined with other methods, such as organosolv, to overcome its limitations and improve overall process efficiency (Itoh et al., 2003). Since biological pretreatment utilises natural microorganisms and enzymes, it reduces reliance on harsh chemicals and energy-intensive procedures (Sahoo et al., 2018), also supporting the circular economy by converting waste into valuable products like biofuels (Brémond et al., 2018). The biological pretreatment for EH proves effective for corn stover and wheat straw (Y. Wu et al., 2021), (Knežević et al., 2021), both yielding higher levels of reducing sugars compared to untreated biomass.

6.2. Hydrolysis processes for LCB

Following the successful conclusion of the pretreatment phase, polymeric carbohydrates, such as cellulose and hemicellulose, undergo hydrolysis to yield monomeric sugars. In the realm of bioethanol production, hydrolysis is a vital step, as the sugars broken down by enzymes during this phase are transformed into bioethanol. This step is essential since the enzymes required for fermentation are capable of breaking down only sugar monomers. The

hydrolysis process can be facilitated by either acid or enzymes (Offei et al., 2019). Hydrolysis without preceding pre-treatment yields typically less than 20%, whereas yields after pre-treatment often exceed 90% (Hamelinck et al., 2005)

6.2.1. Acid Hydrolysis

Acid hydrolysis is a chemical reaction where compounds like cellulose or other polysaccharides are decomposed into their basic monosaccharide units with the aid of an acid catalyst. This process facilitates the conversion of complex carbohydrates into simpler sugars that can then be fermented into ethanol. The most widely utilised method for this is acid-catalysed hydrolysis, which can be concentrated or diluted acids. Typically, sulfuric acid (H_2SO_4) and hydrochloric acid (HCl) are the acids of choice. When using concentrated acid, the hydrolysis occurs at lower temperatures and with high acid concentrations, achieving a sugar recovery rate of 90% in a relatively short time (Marett et al., 2017)

6.2.1.1. Dilute Mineral Acid Hydrolysis Method

A dilute solution of sulphuric acid can be employed to convert hemicellulose into xylose in a continuous-flow reactor, operating at elevated temperatures near 488K (Graf et al., 1987). The procedure of dilute acid hydrolysis is bifurcated into two distinct stages to capitalise on the differential thermal stability of hemicellulose and cellulose. The initial stage is executed at a lower temperature to optimise the extraction of hemicellulose-derived sugars. Conversely, the subsequent stage is conducted at a higher temperature, tailored for the hydrolysis of cellulose (Brennan & Wyman, 2004). Pentose sugars are recovered in the first stage, while through rigorous conditions, the second stage recovers hexose sugars (Demirbas, 2006). The two most significant advantages of (DMAH) compared to EH are its remarkable capacity to infiltrate the complex lignin architecture without requiring extensive pretreatment, and its impressive rapidity (Bekele Bayu et al., 2022). This dual prowess not only streamlines the process but also enhances efficiency, allowing for a more effective breakdown of biomass. With DMAH, the barriers presented by lignin become less daunting, paving the way for a swifter and more accessible conversion of materials.

In addition, the method stands out as a more economical option when juxtaposed with

enzyme-based techniques and alternative approaches. This advantage primarily arises from the robust market that exists for the production and application of potent acid catalysts. Furthermore, the financial burden is lightened even more by the fact that these catalysts are utilised in minimal concentrations, ranging from 0.01 to 0.90 M (Trivedi et al., 2015). The strategic use of low concentrations not only enhances efficiency but also underscores the method's appeal, making dilute acid hydrolysis a compelling choice for solutions in chemical processes.

6.2.1.2. Concentrated Mineral Acid Hydrolysis (CMAH)

CMAH operates at relatively low temperatures, with the only pressures involved being those needed to move materials from one container to another. Unlike the dilute acid method, the reaction times for the concentrated acid process are generally much longer (Graf & Koehler, 2000). This method specifically employs 70% sulphuric acid and keeps the temperature between 313 and 323K, lasting anywhere from 2 to 4 hours in a reactor. By keeping temperatures and pressures low, the goal is to reduce sugar degradation during the process. After the initial hydrolysis stage, the material is washed to help recover the sugars. The next step involves depolymerising the cellulose fraction. The solid residue from the first phase goes through de-watering, and then it's soaked in a solution of 30 to 40% sulphuric acid for about 50 minutes at 373K to enhance cellulose hydrolysis (Chandel et al., 2007). A significant merit linked with CMAH is its potential to achieve high efficiency in monomeric sugar recovery (Demirbaş, 2005). Nonetheless, it is important to note that while the use of strong acids proves effective in reducing the crystallinity of cellulose, it also brings about the simultaneous degradation of monomeric sugar (glucose). Using concentrated acids (sulfuric and hydrochloric acid) can lead to greater cost savings compared to using diluted sulfuric acid (Farooqi & Sam, 2004). However, working with concentrated sulfuric or hydrochloric acid can be tricky. To make the process financially viable, it's crucial to recover and concentrate nearly all of the acid involved.

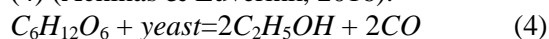
6.2.1.3. EH

It is a process that uses enzymes to break down complex carbohydrates into simpler sugar molecules (Demirbaş, 2004). This method takes

place under mild conditions, typically at temperatures between 45°C and 50°C and a pH level of around 4.8 to 5.0. The enzymes used are proteins derived from plants, and they help to drive specific chemical reactions necessary for this breakdown. The enzymatic breakdown of LCB is notably slow due to the influence of structural factors such as the presence of lignin and hemicellulose, surface area, and the degree of cellulose crystallinity (Pan et al., 2006). The appeal to use EH stems from its cost-effective application, mild operation conditions (mild temperatures, pressure and pH) and non-corrosion issues (Sun & Cheng, n.d.). Enzyme hydrolysis can breakdown agricultural residues like pretreated wheat straw with Advanced Enzyme (AD), Novozyme (CL), and Genencor (AC) (Agrawal et al., 2018), SCB with *Trichoderma Reesei* MTCC 3194 (Agrawal et al., 2018), pretreated cassava peels with *Aspergillus Niger* (A.N) (Adetunji et al., 2016), and cassava/sweet potato peels with *Gloeophyllum sepiarium* and *Pleurotus ostreatus* (Oyeleke et al., 2012).

6.3. Fermentation methods of cellulosic ethanol production

Fermentation, which is a crucial metabolic process undertaken by microorganisms, involves the conversion of soluble sugars into alcohol. The biological process is expressed as equation (4) (Achinas & Euverink, 2016).



Some specific types of bacteria and yeasts possess the ability to metabolise both monosaccharides (such as glucose and fructose) and disaccharides (like maltose and sucrose) in anaerobic conditions, leading to the production of ethanol and carbon dioxide as by-products (Zabed et al., 2017). The hydrolysates derived from lignocellulosic biomass contain a combination of pentose and hexose sugars. Currently, xylose-fermenting bacteria encompass both naturally occurring strains and genetically modified organisms, many of which possess advantageous characteristics for simultaneous saccharification and fermentation processes (Hahn-Hägerdal et al., 2006). While hexose sugars like glucose, galactose, and mannose are commonly fermented by a range of naturally existing microorganisms, notably *Saccharomyces cerevisiae* and *Zymomonas mobilis*, certain yeast strains like *Pachysolen tannophilus*, *Pichia stipitis*, *Kluyveromyces marxianus*, and *Candida shehatae* exhibit the ability to ferment xylose

(Delgenes et al., 1986). The utilisation of *Saccharomyces cerevisiae* has been explored in various studies, including its application on pretreated and hydrolysed corn cob (Samuel et al., 2010), as well as in a co-culture setup with *Aspergillus niger* for the SSF of dry pre-treated corn cob at concentrations of 1% and 10% (w/v) (Ado et al., 2009). Additionally, *Saccharomyces cerevisiae* has shown promise in fermenting milled yam peels (*Dioscorea rotundata*) (Bashir et al., 2022).

The commonly used technologies for the fermentation of monomeric units of sugar to ethanol include separate hydrolysis and fermentation (SHF), simultaneous saccharification and fermentation (SSF), and simultaneous saccharification and co-fermentation (SSCF).

In the SHF process, EH is conducted independently from fermentation. This separation permits the enzymes to function at elevated temperatures, while the fermentation microorganisms operate at their ideal moderate temperatures, thus optimising their respective performances (Mohd Azhar et al., 2017). Due to the enzymes and microorganisms working under optimal conditions, a higher ethanol yield is anticipated. However, SHF is associated with certain drawbacks, such as increased capital expenditure due to the necessity for dual reactors, prolonged reaction times, and potential inhibition of cellulase activity by the sugars generated during hydrolysis (Erdei et al., 2012).

In the context of (SSF), the enzymatic breakdown of cellulose and the subsequent fermentation of the resultant sugars occur concurrently within a single bioreactor (Rastogi & Shrivastava, 2017). This concurrent utilisation of the hydrolysate for fermentation circumvents the typical suppression of cellulase activity (Sakamoto et al., 2018). However, a notable limitation of SSF is the discrepancy between the optimal temperatures necessary for the maximal efficacy of cellulase enzymes and the fermentative microorganisms. Specifically, the elevated temperatures that facilitate cellulase-mediated hydrolysis may adversely affect the viability of fermentative yeasts.

The SSCF method combines hydrolysis and saccharification in one device, allowing for the simultaneous co-fermentation of pentose sugars. This process primarily utilises genetically modified strains of *Saccharomyces cerevisiae* that can metabolise xylose, unlike conventional strains that do not possess this capability

(Bondesson & Galbe, 2016). Analogous to SSF, SSCF presents benefits such as reduced expenses, augmented ethanol production, and diminished duration of processing (Koppram et al., 2013; Ojeda et al., 2011). Furthermore, SSCF is instrumental in curtailing sugar-induced inhibition during EH and elevates the xylose-to-glucose concentration ratio, given that a majority of microorganisms preferentially consume xylose (Sharma et al., 2021).

Another existing fermentation technique is the Consolidated Bioprocessing (CBP), which requires the enzyme production, hydrolysis and fermentation to be carried out in a single unit. The microorganism mostly used in this process is *Clostridium thermocellum*, as it can synthesise cellulase, which degrades lignocellulose to monomeric sugars and produces ethanol (Hasunuma & Kondo, 2012). Although CBP is still at its nascent stage, the following advantages have been identified: less energy-intensive, cheaper cost of enzyme, lower cost of investment, and less possibility of contamination.

6.4. Ethanol Separation and Dehydration Methods

Following the successful fermentation of monomeric sugars to bioethanol, a crucial downstream processing step is the efficient recovery of ethanol from the resulting fermentation broth. This process typically aims to achieve a final ethanol concentration exceeding 99.5% by volume, corresponding to an anhydrous product with minimal water content (around 0.5% by volume). Anhydrous ethanol represents a prominent biofuel within the broader category of renewable energy sources. Due to its clean-burning characteristics, it is considered a viable alternative to gasoline as a transportation fuel (Kumar et al., 2009). However, the separation of ethanol from the fermentation broth presents a significant challenge due to the formation of an azeotrope with water. An azeotrope is a constant boiling point mixture, where complete separation by conventional distillation is not achievable (Rackley, 2010). To overcome this limitation, various ethanol recovery techniques have been established, all leveraging the principle of distillation but employing different strategies to manipulate the relative volatility of the components.

The existing ethanol recovery methods are adsorption distillation, azeotropic distillation (with an entrainer), and extractive distillation, which are all conventional methods (Nitsche &

Gbadamosi, 2017). Currently, extractive distillation stands as the dominant approach for large-scale bioethanol production. However, a growing interest exists in exploring alternative techniques that offer the potential for lower energy consumption. Pervaporation and salt distillation are among the recovery techniques that are gaining attention as viable alternatives for future applications (Nagy et al., 2015).

Liquid-liquid extraction is a separation technique used to isolate ethanol from fermentation broths (Weilhammer & Blass, 1994). A hydrophobic solvent is introduced into the bioreactor, allowing ethanol molecules to migrate from the broth into the solvent. The solvent used should be effective, chemically inert, hydrophobic, and non-toxic (Antony & Wasewar, 2020). After the two phases come into contact, the product of interest partitions between the two phases, establishing an equilibrium distribution between the solvents. This method is used in various applications to recover desirable materials or remove unwanted impurities from liquid mixtures (Prasad & Sirkar, 1992).

Pervaporation involves the partial vaporisation process to distinguish between the elements of a mixture. In this method, a membrane acts as a selective barrier, allowing certain components to pass through at unique diffusion rates. The mixture interacts with one side of the membrane, while a specific component is allowed to permeate and transition into the vapour phase on the opposite side (Luis, 2018; Nagasawa & Tsuru, 2017). This method has demonstrated impressive capabilities, including the ability to obtain concentrated ethanol from various sources, such as juice from sorghum (Kaewkannetra, 2012), RS, and SCB (Pham et al., 2023).

7. Cellulosic Ethanol Production in Nigeria: The Challenges and Opportunities

Biofuels, including bioethanol and gasohol, are increasingly regarded as instrumental in addressing global energy dilemmas, fostering rural advancement, and combating climate change. Nigeria, Africa's most densely populated nation and a significant consumer of automotive fuels, has acknowledged the benefits of establishing a substantial bioethanol sector. In alignment with this, Nigeria aspires to align with other biofuel-manufacturing countries through a formal directive issued to the Nigerian National Petroleum Company in 2007, which mandates the establishment of a framework for the biofuel

production enterprise within the nation. This initiative focuses on cutting over-dependence on imported petroleum products and reducing the ecological footprint. The emphasis on bioethanol production, which, when amalgamated with gasoline, yields gasohol—a more ecologically benign and renewable energy source—introduces many impediments and prospects. Surmounting these critical issues is crucial to expediting the large-scale production process.

7.1. Challenges of Bioethanol / Gasohol Production in Nigeria

One of the pressing issues facing Nigeria's bioethanol and gasohol production sector is the availability and consistency of feedstock supply. The country's ethanol production largely relies on cassava and corn as primary feedstocks (Ohimain, 2013a). Exploring the vast biomass resources for commercial production of biofuel (bioethanol) in Nigeria is a controversial issue, because it proposes first-generation biomass as feedstock for large-scale ethanol production. This adoption could cause food security to be threatened because sugar and starch-rich crops (cassava, corn and sugarcane) may be diverted into biofuel production, which could cause a food crisis eventually. For instance, the NNPC conducted feasibility studies on ethanol and biodiesel production using major Nigerian staple crops, including cassava, sugarcane and palm oil as feedstock. It also started a series of discussions with willing investors, which resulted in the flag-off of the building of a score and fourteen bioethanol factories (Ohimain & Izah, 2017) set to rely on first-generation feedstock for the production of biofuels (Abila, 2012). This created the challenge of sustaining the production of the required feedstock, given the parlous state of food security in Nigeria. However, in Brazil, there is no conflict between food and energy (Gauder et al., 2011), and this is possible if there are investments in the countryside, which can result in increased agricultural productivity and improved production of food in parallel with agro-energy [(Nasidi et al., 2010). However, the potential impact of biofuel development on food security should be thoughtfully evaluated in any biofuel initiative. Additionally, Nigeria should investigate alternative low-yield biomass feedstocks that are plentiful within the nation. (Agbro & Ogie, 2012). While Nigeria has the potential to cultivate these crops on a large scale, owing to its abundant arable land and

favourable climate, the reality on the ground tells a different story. Seasonal variations, pests, and diseases often plague sugarcane and cassava production in Nigeria, which can disrupt the steady flow of raw materials to ethanol plants (Ohimain, 2010). This volatility in feedstock supply can have a detrimental impact on the economic viability of ethanol production, as producers struggle to maintain consistent output and profitability.

The overarching objective of the Bio-fuel Production initiative is to accomplish the total domestic output of biofuels consumed nationally by the year 2020. It is unmistakably clear that a substantial amount of acreage would be necessary to fully satisfy the demand for biofuel under the automotive biofuel scheme. Acquiring a large expanse of land necessary for crop cultivation will inevitably result in the displacement of farmers from their lands. The magnitude of arable land required for cultivating these crops is indeed immense, consequently demanding substantial quantities of energy and water as essential inputs (Ohimain, 2013b). Viewed from an alternative standpoint, Nigeria possesses a substantial expanse of arable land suitable for cultivating energy crops like cassava and sugarcane; nonetheless, the primary challenge lies in the allocation of these lands for the growth of energy crops intended for biofuel production. This allocation process ultimately creates competition with land designated for food production, thereby jeopardising food security within the region. The inadequacies in the nation's infrastructure further impede the comprehensive development of bioethanol production. Deficiencies in transportation networks, power supply, as well as storage and distribution facilities, often prove to be inadequate, thereby impeding the efficient transportation of raw materials and finished products, which will affect the operation of ethanol plants. (Ohimain, 2013b). These gaps in infrastructure contribute to the escalation of production costs, thereby diminishing the profit margins of ethanol manufacturers and rendering it challenging for them to compete with the pricing of imported petroleum-derived fuels.

7.2. The Opportunities and Recommendations

Nigeria's bioethanol-based automotive fuel sector, despite encountering significant challenges, presents a vast array of opportunities. The country's expansive agricultural sector

generates millions of tons of waste and residue annually, which could be effectively utilised for bioenergy production. This possibility not only presents a promising avenue for diversifying energy sources but also functions as a method to lessen reliance on traditional fossil fuels through the implementation of appropriate policies, substantial investments in infrastructure, and continuous technological advancements. Nigeria has the potential to significantly boost its feedstock production, which can in turn ensure a more stable and consistent supply to its ethanol plants, thereby fostering growth and sustainability in the sector. The biofuel industry in Nigeria can contribute significantly to environmental sustainability by diminishing the carbon footprint and addressing the shortcomings associated with conventional energy sources. The application of bioenergy derived from agricultural waste represents a pivotal step towards energy diversification and is in alignment with ongoing environmental conservation endeavours. A thorough examination of the synthesis of the biofuel industry in Nigeria emphasises the substantial opportunity for bioenergy to function as a workable answer to the nation's energy demands, as long as the existing resources are efficiently utilised and technological progress persists. Furthermore, with Nigeria's population and economy on a continual growth trajectory, the domestic demand for transportation fuels is poised to rise, creating a robust market for ethanol-blended gasoline. This escalating demand, coupled with the environmental advantages linked to ethanol consumption - notably reduced carbon emissions within the transport sector- could serve as a compelling driver for the Nigerian government to make advancement of the ethanol and gasohol industry a priority. Such initiatives are integral to achieving broader sustainability objectives and enhancing energy security within the nation. The acknowledgement of the complete potential of ethanol and gasohol production in Nigeria mandates a comprehensive strategy that adequately handles the different challenges affecting the industry. This thorough strategy might involve targeted investments in infrastructure improvement, the establishment of clear and consistent regulatory frameworks, the promotion of public-private partnerships to encourage innovation, and the examination of alternative sources of feedstock to lessen risks linked with excessive dependence on a single

crop. By surmounting these problems and capitalising on the possibilities, Nigeria has the potential to establish itself as a major player in the commercialisation of ethanol and gasohol within the region, leading to advancements in its energy stability, financial progress, and ecological sustainability. Although the road ahead may present complexities, the potential benefits are substantial, urging the nation to remain resolute in its dedication to cultivating a prosperous biofuel sector that can set an example for other nations across Africa. Nigeria's ideal positioning in the biofuel sector may not only strengthen its economy but also function as a model for sustainable growth in nearby African nations, underscoring the significance of ongoing dedication and persistence in this field.

8. Conclusions

The critical examination provided in this review is focused on the current biomass reservoirs available in Nigeria, specifically highlighting their potential for use in producing various types of biofuels. The analysis demonstrates a significant opportunity for transforming these resources into a variety of biofuels by employing a range of existing biomass conversion technologies. Nigeria emerges as a nation with immense prospects for cultivating energy crops that can be leveraged for bioethanol and biodiesel production. Statistics available underscore Nigeria's primary position in growing indispensable energy crops such as soybean, palm oil, sesame, cassava, sugarcane, and sorghum. Moreover, the abundance makes them ideal for serving as feedstocks for bioethanol-based automotive fuels. In addition, the fusion of the natural segment of municipal solid waste (MSW) with animal excrement could have a minimal impact as a potential cellulosic supply for biogas manufacturing. Nigeria presently faces a situation where it heavily relies on imported transportation fuel, exposing the nation to risks associated with fluctuations in global fuel prices and requiring foreign exchange to meet domestic energy needs. Consequently, the primary aim is to reduce the substantial dependence on imported petroleum by maximising the utilisation of local biomass resources for biofuel production, specifically emphasising bioethanol-based automotive fuel. However, it is crucial to pursue this objective sustainably, considering the potential minimal environmental and socio-economic impacts that could arise from such initiatives.

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