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Decarbonizing Vehicle Transportation with Hydrogen from Biomass Gasification: An Assessment in the Nigerian Urban Environment

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Abstract: Tailpipe emissions from vehicles consist of CO_2 and other greenhouse gases, which contribute immensely to the rise in global temperatures. Green hydrogen produced from the gasification of biomass can reduce the amount of CO_2 emissions to zero. This study aims to provide a modelling framework to optimize the production of hydrogen from biomass waste obtained from different cities, for use in the road transport sector in Nigeria. A gasification model with post-treatment shift conversion and CO_2 removal by adsorption is proposed. In this study, six cities are simulated based on technical and environmental considerations, using the Aspen Plus software package. The results revealed that Kaduna has the highest hydrogen generation potential of 0.148 million metric tons per year, which could reduce CO_2 emissions to 1.60 and 1.524 million metric tons by the displacement of an equivalent volume of gasoline and diesel. This amounts to cost savings of NGN 116 and 161.8 billion for gasoline and diesel, respectively. In addition, the results of the sensitivity analysis revealed that the steam-to-biomass ratio and the temperature of gasification are positively correlated with the amount of avoided CO_2 emissions, while the equivalence ratio shows a negative correlation.

Keywords: biomass; gasification; green hydrogen; carbon dioxide emissions; Aspen Plus; simulation; Nigeria

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1. Introduction

The global energy demand in 2020 was estimated to be 557 exajoules (EJ), of which 31.2% and 27.2% are met by oil and coal resources, respectively, representing the largest contributions [1]. CO_2 emissions are primarily driven by economic growth, which requires the consumption of fossil fuels. To achieve a more than 60% chance of limiting global average temperatures to 1.50 °C by 2050, there must be a drastic reduction in the amount of CO_2 gas released into the atmosphere, from current levels to zero [2,3].

According to the International Energy Agency (IEA), global CO_2 emissions increased from 20.5 billion tonnes to 31.5 billion tonnes during the years 1991 to 2020. The amount of CO_2 emitted globally was estimated to be 33 billion tonnes in 2021, and the power industry remains the largest contributor to these emissions by sector. The transportation and industrial sectors also contribute significant amounts. The transportation sector represents 28.9% of the total final energy consumption across the world and 21.9% (7.245 Gt CO_2) of the global CO_2 emissions [4,5].

Road transportation represents the largest share of the energy consumed in the transportation sector, accounting for 75% of the total CO_2 emitted. This is attributed to the combustion of fossil fuels in internal combustion engines (ICE), with gasoline and diesel dominating the fuel mix. Gasoline is used mainly in light-duty vehicles for the movement of people, while diesel is used predominantly in heavy-duty trucks for the movement of goods. With regard to the fuel mix in the United States (USA), gasoline accounts for

62% of the total transportation energy, while diesel and jet fuel contribute 24% and 10%, respectively [6].

In the European Union (EU), road transportation contributes 21% of the total CO_2 emissions, with the incremental sale of diesel fuels peaking at 74% in 2016 [7]. The continuing dominance of fossil fuels in the transportation industry, coupled with incremental sales of internal combustion engines, has prompted the top energy consumers such as the United Kingdom (UK), China, the US and the EU member states to derive strict environmental standards for CO_2 emissions [8,9]. The EU vehicle emission standards are generally adopted as the yardstick for measuring emissions in many countries in the OECD (Organisation for Economic Co-operation and Development) and other developed countries across the globe [10]. The EU vehicle emission standards are classified as part of a group of EU directives that include strict measures at different stages (Euro I, II, III, IV, V and VI) [11–14]. Tailpipe emissions from vehicles include carbonaceous particulate matter (PM 2.5), nitrogen oxides (NOx), Carbon monoxide (CO), CO_2, hydrocarbons (THC) and some volatile compounds. The EU directive 2019/631 establishes EU-fleet CO_2 emission standards for four-wheeled passenger cars and light commercial vans and vehicles (LCVs), thereby replacing previous regulations (EC) No 443/2009 and (EU) No 510/2011 [12,14,15]. In this directive, four-wheeled passenger vehicles and LCVs are restricted to 95 g CO_2/km and 147 g CO_2/km, respectively. The directive establishes 2021 as the baseline for achieving a 15% reduction by 2025 and 37.5% by 2030 for cars, while target reductions of 15% and 31% for the years 2025 and 2030 are also included [13].

Other countries such as China and Australia have harmonized their countries' regulations to accommodate the EU vehicle emission standards [16]. After the Brexit transition period, the UK made slight changes to include an independent regime for CO_2 pooling arrangements. This arrangement was made under the draft statutory instrument Road Vehicle Emission Performance Standards (EU Exit) Regulations 2020, while most of the EU directive 2019/631 remains applicable in the country [15].

The UK and several countries around the globe have made commitments to halt the sale of ICE vehicles between 2025 and 2040 and have resolved to build infrastructures and improve the share of hydrogen fuel cell vehicles (FCEVs), hybrid electric vehicles (HCVs) and electric vehicles (ECVs) in the transport sector [17].

The development of electromobility is measured by the level of proliferation of electric vehicles in the road transportation sector, and there are economic, social and technical factors that influence the growth rate of electric vehicles across the globe. The cost of investment, cost of electricity, infrastructure facilities for charging, local policies and the presence of an effective supply chain remain some of the major factors to consider. According to the IEA [18], the growth of electric vehicles across the globe peaked at 10 million in 2020, which represents a 43% increase over the number registered in 2019. China accounted for the largest share of the market, which is estimated to generate USD 358 billion by 2027 [19]. Europe and North America accounted for 40% of the market share in 2019, while Europe experienced the largest yearly increase of 3.2 million registered electric vehicles. Over the years, the regions of Asia-Pacific, North America and Europe have witnessed an increase in the proliferation of electric vehicles, which is related to their economic growth [20]. On the other hand, little progress has been made in the uptake of electric vehicles in developing countries due to the inability to overcome the financial, technical and political barriers [21,22].

The proliferation of FCEV technology is dependent on the technological advancement of the hydrogen gas market [23]. Hydrogen gas is an energy carrier with a high energy content, and when input into a fuel cell it generates the electricity that is required to power an FCEV. Alternatively, it can undergo combustion in hydrogen internal combustion engines (HICE), either as a single product or mixed with fossil fuels [24]. Hydrogen is advantageous because its general application contributes to the achievement of zero emissions in the transport industry. However some nitrogen oxides are emitted when it is combusted in ICE vehicles, though the NOx (nitrogen oxide) compounds can be removed through the application of selective catalytic reduction (SCR), changing the stoichiometric ratios for fuel combustion and making engine modifications [25]. On the production side, a major issue is that hydrogen does not occur naturally in nature, so its production is dependent on the utilization of fossil sources, water and biomass [26]. The hydrogen produced from fossil fuels contributes about 900 million tonnes (Mt) of CO_2 emissions per year and represents about 80% of the global hydrogen production using steam reformation technology [27]. The electrolysis pathway currently produces 30 kT per year, supplying 0.03% of the total global hydrogen demand, which remained at 90 Mt in the year 2020. The electrolytic process is expensive, with the cost of production at USD 3–5.5 per kg of H_2 [28]. The hydrogen obtained from the electrolysis of water using a photoelectrochemical pathway has the potential to generate zero emissions when major sustainable energy sources (e.g., wind and solar) are utilized. However, the variability and the unpredictable nature of renewable energy sources pose a major challenge for this production pathway [29]. Hydrogen obtained from biomass is recently gaining momentum as a plausible solution that balances the requirements of variability and zero emissions, which are lacking in the available sources already highlighted.

1.1. Literature Connected to This Study

Modelling of the process that involves the gasification of biomass to produce hydrogen can be carried out with the use of simulation software such as Aspen Plus, MATLAB and CHEMCAD, which save time by making it easier to perform sensitivity analyses on different parameters than in real-life or experimental studies. The major advantage of Aspen Plus is its ability to simulate different processes and conditions, using techno-economic analysis. In the gasification process, there are operating conditions and factors such as the steam-to-biomass ratio (STBR), equivalence ratio, feedstock blend and gasification temperature which are important in the optimization of the system [30].

The literature on syngas production from the gasification of biomass includes simulation and experimental studies [31,32], which examine the effect of different operating conditions on the product yield.

The effects of operating parameters on the updraft gasification of biomass were determined in this study, revealing that the best results were obtained within the range of 0.23–0.27 for the value of the equivalence ratio [32]. The effect of the gasification temperature on the biomass gasification process was also investigated in this study, revealing that increasing the gasification temperature from 700 °C to 900 °C led to an incremental increase in synthesis gas yield and a lower heating value (LHV), tar content and cold gas efficiency (CGE) [33]. Fremaux et al. [34] conducted a gasification process by including steam as the agent and revealed that the addition of steam improved the content of H_2 in the syngas when the steam-to-biomass ratio was increased from 0.5 to 1.0. However, changing the steam-to-biomass ratio from 0.8 to 1 resulted in a decrease in the steam reformation reaction process, thereby affecting the yield of hydrogen. This was also evident in the study carried out on an updraft gasifier [32]. This further demonstrates that excess steam lowers the gasification temperature, thereby reducing the gas quality. In this study, the optimum steam-to-biomass ratio was selected as 0.8. Some studies have used Aspen Plus software to create a kinetic equilibrium model in a Gibbs reactor to predict the effect of the operating parameters on syngas composition [33,35–38]. Other studies focused on the modelling of tar production according to the kinetic and thermodynamic equilibrium [39,40].

Generally, the gasification process is split into four stages, including one exothermic reaction (oxidation) and three endothermic reactions (drying, pyrolysis and reduction) [41]. Syngas is the primary product obtained from the gasification process, and the overall efficiency of the system can be improved by converting the syngas to multiple products such as heat, power and biofuels [42–47]. Improving the efficiency of the system maximizes the production of syngas. Recently, some studies have used technical, environmental and economic factors to evaluate the performances of polygeneration and cogeneration systems used to optimize the production of hydrogen. Hamrang et al. [47] performed energy, exergy and economic analyses on an integrated biomass gasification system to evaluate the system performance with regard to electricity and fresh water production. Kowsari et al. [48] investigated the selection of optimal stations for the production of hydrogen, by analyzing the energy and eco-exergy attributes of the system. The results revealed that the stations which have inlet-gas mass flow rates within the range of 8–9 kg/s were preferentially selected. Hekmatshoar et al. [49] performed a thermo-economic analysis to obtain an optimal geothermal system for the production of hydrogen, where a multi-criteria decision method (TOPSIS) was used to rank the available options. The system also produced power and fresh water. Alnouss et al. [50] conducted a techno-economic and environmental analysis on different blends of waste to optimize the production of hydrogen. Technical evaluations of three gasification systems for producing power, heat and syngas were conducted in this study [45].

This study conducted a techno-environmental evaluation of sites to select the optimal sites for maximizing the production of hydrogen through the process of gasification.

1.2. Motivation for This Study

In developing countries, it is expected that the rate of waste generation will more than triple by 2050, and at this rate, the risks to the environment and the health of inhabitants are enormous, given that current waste management practices are not guided by legislation on proper use and disposal [51,52]. Therefore, this paper proposes the conversion of waste to energy, as a solution to this problem. In this paper, the thermal gasification process is detailed, and the hydrogen gas produced is optimized through the use of a post-treatment water–gas shift reaction, a CO_2 absorption process and the consideration of operating parameters.

1.3. Novelty of This Work

To the best of the authors' knowledge, this study is the first study in Nigeria that performs an analysis of different sites for the optimal production of hydrogen. In this study, hydrogen production from six sites is simulated with the use of the Aspen Plus software, and a comparative analysis of their performance under technical, environmental and economic considerations is conducted with the objective of obtaining the optimum site that can be recommended to policymakers and decision-makers. The main objectives of this work are:

1. Simulating the biomass waste in six sites with various mass flow rates in Aspen Plus, to produce hydrogen.
2. Analysis and comparison of the different sites using technical and environmental factors.
3. Determining the effect of the optimum operating conditions on the amount of CO_2 emissions from the road transport sector from the gasification process.

This study contributes to the body of knowledge on the effective utilization of waste resources to provide energy. Biomass gasification technology provides a sustainable alternative to the current practice of open burning in Nigeria. The importance of this study lies in countrywide analysis of the road transport sector, offering more insight into implementing CO_2 reduction strategies in the country.

The rest of this paper is structured as follows. Section 2 presents the biomass resources in Nigeria and the study area, including a description of the vehicle fleet composition and the energy demand in the road transport sector. Section 3 describes the methodology in detail. The results are detailed and discussed in Section 4. We finally conclude in Section 5.

2. Biomass Waste to Energy for Transportation in Nigeria

Biofuel is a suitable substitute for fossil fuel consumption in the Nigerian road transport sector. When biomass feedstocks are synthesized, they can be used to produce bioethanol, biodiesel and biogas.

The biomass resource in Nigeria is estimated to be 200 million tonnes per year [53]. Biomass feedstock in Nigeria is generally obtained from agricultural resources, municipal waste, industrial waste and forest waste sources.

According to the Food and Agricultural Organization (FAO) [54], Nigeria is the world's largest producer of cassava, producing about 60 million tonnes in 2019 [55,56]. Cassava peels are non-edible and have a high energy content of 10.61 MJ/kg, with a 50% moisture content [57]. Cassava peels contain lignocellulose, which produces ethanol when subjected to a fermentation process [58]. Nigeria produces 14 million tonnes of cassava-peel waste [59].

The majority of the biogas available as a transport fuel in Nigeria is obtained from municipal waste in landfills and anaerobically digested industrial wastewater, with the former being the most popular source for biogas production. Nigeria generates 25–45 million tonnes of solid waste in a year [60].

Biodiesel in Nigeria is mainly obtained from palm oil, which accounts for 10% of biodiesel production in the world. Nigeria is notable for being the fifth-largest producer of palm oil in the world, producing 930,000 metric tons, representing 1.5% of the global production [61,62]. Palm fatty acid is subjected to an esterification process with the addition of ethanol/methanol to produce fatty acid methyl ester, which meets the standard requirements for biodiesel.

Nigeria generates 83.01 million tons of animal waste per year, and the majority of this is obtained from cow dung and poultry litter [55].

Wood chips from sawmills contain cellulose. The Fischer–Tropsch process converts wood biomass into synthesis gas (syngas), which is used to produce synthetic crude oil via the catalytic polymerization and hydrogenation of carbon monoxide. The synthetic crude is further refined to produce various fuels used in the road transport sector. Nigeria has 2631 million metric tons of forest biomass [55]; however, considering issues of deforestation and concern for wildlife, this biomass feedstock is not a popular option.

Nigeria is Africa's largest producer of crude oil, producing about 1,365,000 barrels daily, 75 per cent of which is consumed in the transport sector. Diesel and petrol are the major contributors to the energy demand by fuel source in the road transport sector. The Nigeria National Petroleum Corporation (NNPC) estimated the daily consumption of gasoline and diesel in the country in December 2020 to be 75.1 million L and 380 thousand L, respectively [63–65]. Biofuel production in the world reached about 151 billion L in 2021, though biofuels such as ethanol and biodiesel are not popular for use in vehicle transportation in Nigeria, as a result of inadequate production infrastructures and weak government policies [62].

In the year 2018, the number of vehicles in Nigeria was estimated to be 11,760,871, from the fourth-quarter report (Q4) by the National Bureau of Statistics (NBS) [66]. The fourth-quarter report estimated the vehicle-to-population ratio as (0.06), i.e., 6 vehicles per 100 persons. The vehicle composition in Nigeria is shown in Figure 1.

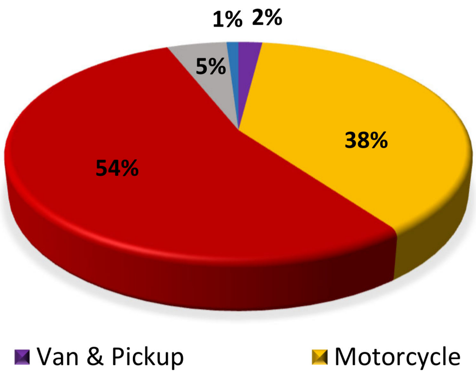

Figure 1. Vehicle fleet composition obtained from [67].

The cities are distributed across the geopolitical zones of the country. The locations of the selected cities are shown in Figure 2, and details are provided in Table 1. In Nigeria, there are three geopolitical zones in the northern region (the northeast, north central and northwest zones) and three geopolitical zones in the southern region (the south-south, southeast and southwest zones). The cities were selected based on their internally generated revenues (IGRs), which were validated by the NBS [66]. It is assumed in this study that vehicle ownership increases with an increase in the value of the internally generated revenues of the cities. Internally generated revenue has a positive relationship with the real gross domestic product [68].

Figure 2. Map of Nigeria showing the cities' locations.

Table 1. Statistical data for the selected cities.

Selected City	IGR [66]	Population (p) [69]	Vehicle Owners (v) $v = p \times 0.06$	Waste Generated per Capita (kg/Capita/Day)
Abuja	69,072,879,664	1,406,239	546,816	0.634 [70]
Enugu	14,140,554,676	3,267,837	311,922	0.48 [71]
Port-Harcourt	57,324,672,372	5,198,716	196,070	0.22 [72,73]
Lagos	267,232,774,434	9,113,605	84,374	0.47 [26]
Kaduna	26,429,424,219	6,113,503	94,926	0.56 [74]
Bauchi	9,467,289,020	4,653,066	279,218	0.22 [75]

3. Methodology

This section provides the formulas and equations used to estimate the amount of hydrogen gas produced from the different biomass feedstocks and the total CO_2 vehicular emissions for each of the selected cities.

3.1. Estimating the Feedstock for Simulating the Biomass Gasification Model in Aspen Plus

Food waste, cow dung and cassava peel were chosen because of their degradability and availability in the selected cities. The feed-blend ratio was 33.3%. The food flow rate value used in the Aspen Plus software was obtained as a percentage fraction of the urban solid waste available in each of the selected cities. The amount of cow dung was estimated from the data provided by the FAO [55].

3.1.1. Calculating the Input Value of Food Waste for the Aspen Plus Model

The mathematical expression used to estimate the amount of food waste is presented below:

$$Food\ waste_{(t)} = F_{frac} \times MSW_{(t)} \times F_{comp} \quad (1)$$

where t is the production duration (from 2022 to 2037), $MSW_{(t)}$ is the quantity of urban solid waste produced in the different locations and F_{comp} is the percentage of organic waste present in the urban solid waste [26].The estimation of the value is guided by parameters that include the population growth rate and by the waste generation model proposed in previous studies. F_{frac} is the collection rate of urban solid waste, which was 0.74, obtained from previous studies [28,76,77]. $MSW_{(t)}$ is given by Equation (2)

$$MSW_{(t)} = \frac{P_{(t)} \times W_{(t)} \times 365}{1000}\ \text{(metric tons/year)} \quad (2)$$

where $P_{(t)}$ and $W_{(t)}$ represent the rates of population growth and the waste generation per capita at a selected reference time t, respectively, and are calculated using Equations (3) and (4)

$$P_{(t)} = P_o\,(1 + r_o)^t \quad (3)$$

$$W_{(t)} = W_o\,(1 + r_{GDP})^t \quad (4)$$

where P_o and W_o are the initial rates for population growth and the waste generation per capita and r_o and r_{GDP} represent the population and the economic growth factor per capita for waste generation, respectively. The value of r_o for Nigeria is taken as 3.2%. The value for the economic growth factor used to measure the per capita waste generated was 3.3% [26,66,78].

The cities were selected based on their internally generated revenue, which is positively linked to the real gross domestic product. The ownership of vehicles is dependent on the income variable of the residents of each city [68]. The value of F_{comp} is obtained by taking the average percentage of food in municipal waste from a previous study, which was 35.82% [75,76].

3.1.2. Estimating the Amount of Cow Dung

The amount of animal waste in Nigeria is taken from previous studies as 83.01 million tons per year. There are 18.4 million head of cattle, which represents 5.78% of the total national herd of 317.8 million livestock animals. It is estimated that the northern region contains 90% of the cattle in Nigeria, and the southern region contains the remaining 10% [55].

3.1.3. Estimating the Amount of Cassava-Peel Waste

From a previous study, it is estimated that 14 million tonnes of cassava peel is produced on a yearly basis in the country [59]. In the absence of regional data on cassava-peel waste for each of the cities in this study, it was assumed that the amount of cassava-peel waste produced from each city was approximately 11.905% of the total amount generated in the country every year. There are a total of 36 municipalities/states in Nigeria, with an average of six states in each of the geopolitical regions.

3.2. Aspen Plus Simulation and Modelling

The simulation process for hydrogen production from food waste, cow dung and cassava peel mixed feedstock is modelled in three stages: the gasification process, the water–gas shift reaction (WGS) and the CO_2 removal stage. Figure 3 shows an overview of the simulation process using the Aspen Plus software. The basic Aspen Plus model was adopted from [45], with a circulating fluidized-bed gasifier (CFBG) as the gasifier type, while the simulation methodology was adopted from [50]. Other process details for hydrogen production plants were taken from [77]. This simulation adds a WGS section to upgrade the syngas formed and maximize the production of H_2. The minimum recommended temperature (230 °C) was selected for the WGS to maximize the production of H_2, since it is an exothermic reaction. The use of fixed-bed sorbents for CO_2 removal is explained in [79]. The global property package for this model was PR-BM [80]. For the optimum case, the steam-to-biomass ratio (STBR) was selected as 0.8 [34,81], while the equivalence ratio was selected as 0.1 [45]. The input specifications and the functions of the equipment (or block) are summarized in Table 2. The proximate and ultimate analyses (see Table 3) were performed with thermodynamic conditions of 1 bar and 25 °C, and the respective mass flow rates were input to the streams for cassava peel, cow dung and MSW.

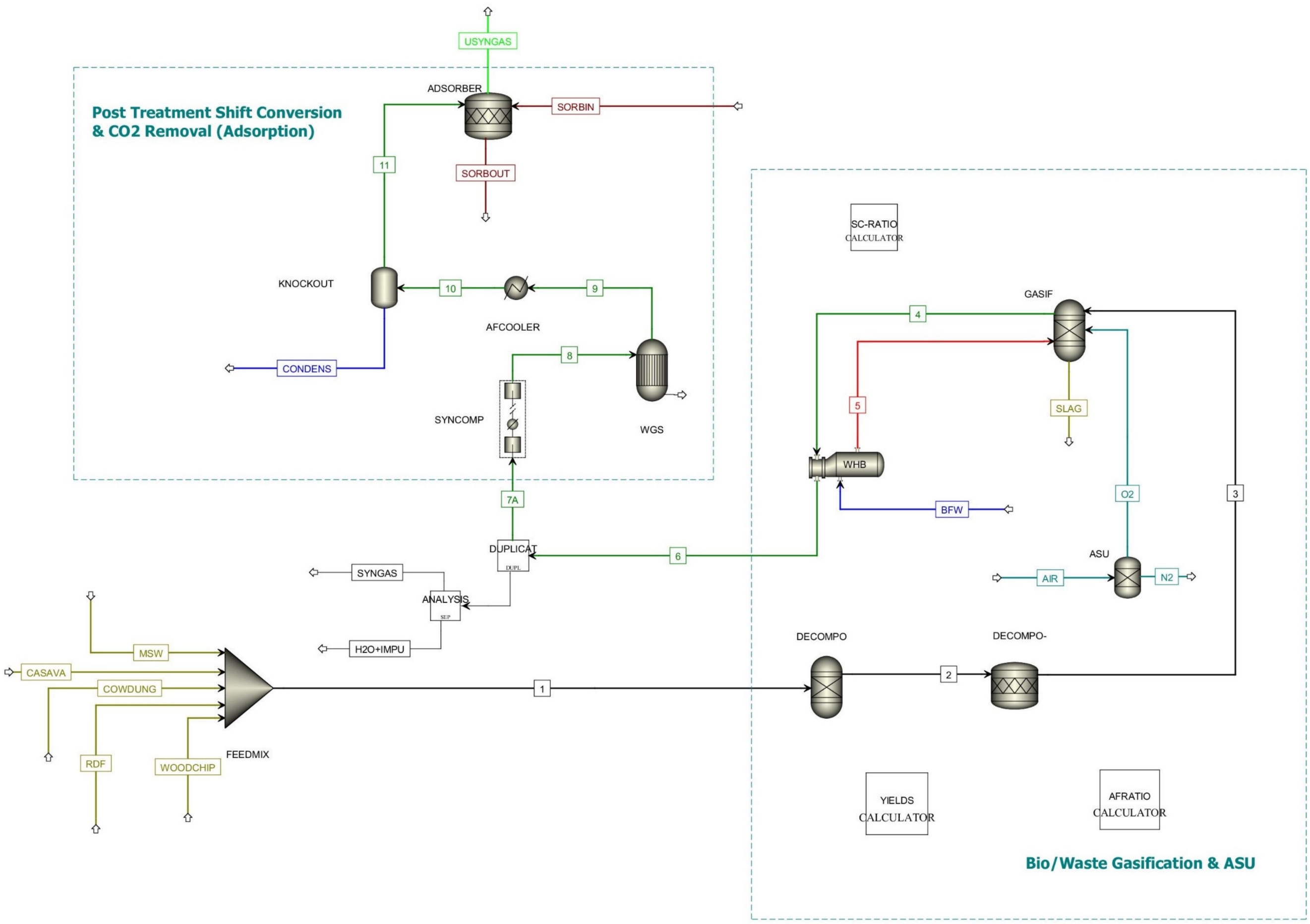

Figure 3. Aspen Plus simulation diagram.

Table 2. Input specifications and function of equipment/block utilized in the simulation.

Equipment ID (Aspen Plus Block)	**Input Conditions and Parameters**	**Function/Details**
FEEDMIX (MIXER)	-	Combines the different streams of non-conventional feeds, i.e., biomass/waste.
DECOMPO (RYIELD)	T = 25 °C, P = 1 bar	Converts the biomass feed into conventional components in the form of constituent elements, ash and water.
YIELDS (CALCULATOR)	Fortran expression	Adjusts the percentage yield input in RYIELD for each element, and for ash and water, according to the incoming mixed feed.
DECOMPO- (RSTOIC)	T = 25 °C, P = 1 bar $N_2 + 3H_2 \rightarrow 2NH_3$ $S + H_2 \rightarrow H_2S$ $Cl_2 + H_2 \rightarrow 2HCl$ Fractional conversion = 1 for S, N_2 and Cl_2	Converts all the sulfur, chlorine and nitrogen into H_2S, HCl and NH_3, respectively.
GASIF (RGIBBS)	Restrict chemical equilibrium—specify temperature approach or reaction extent; T = 850 °C, P = 0 bar (no pressure drop); set H_2S, NH_3 and HCl as inerts with fraction = 1 $C + 2H_2 \leftrightarrow CH_4$ (Temp. approach = 0 °C) $C + H_2O \leftrightarrow CO + H_2$ (Temp. approach = 0 °C) $C + CO_2 \leftrightarrow 2CO$ (Temp. approach = 0 °C) $CH_4 + H_2O \leftrightarrow CO + 3H_2$ (Temp. approach = −265 °C) $CO + H_2O \leftrightarrow CO_2 + H_2$ (Temp. approach = −90 °C)	Carries out steam–air gasification. The reactor predicts products by the principle of minimization of Gibb's energy, while carrying out the specified equilibrium reactions with input temperature approach to equilibrium.
ASU (SEPARATOR)	For O_2 stream, split fraction = 1 for component O_2, while all the rest of the components are set to zero	Splits ambient air into N_2 and O_2 assuming 100% separation (not modelled in detail).
AFRATIO (CALCULATOR)	Fortran expression	Sets the flowrate of AIR stream "equivalence ratio (ER)" times the stoichiometric required air for combustion of same biomass/waste.
SYNCOMP (MCOMPRESSOR)	Isentropic; 2 stages Equal pressure ratio Fixed discharge pressure from last stage = 24 bar Cooler outlet temperature = 230 °C	Carries out multi-stage isothermal compression so that cooled syngas is at the reported pressure for WGS.
WHB (HEATX)	Hot/cold outlet temperature approach = 5 K	Recovers waste heat from the outlet of the gasifier to generate process steam (at 1 bar) from boiler feed water (BFW) at T = 25 °C.
SC-RATIO (CALCULATOR)	Fortran expression	Sets the molar flow rate of BFW "steam-carbon ratio" times the flow rate of methane in the feed.
WGS (REQUIL)	P = 0 bar (no pressure drop) Duty = 0 cal/s $CO + H_2O \leftrightarrow CO_2 + H_2$	Carries out the water–gas shift reaction by taking equilibrium conversion at the specified conditions.
AFCOOLER (HEATER)	T = 25 °C P = 0 bar (no pressure drop)	Cools the syngas to ambient temperature so that nearly all the water is condensed out.
KNOCKOUT (FLASH2)	Duty = 0 cal/s P = 0 bar (no pressure drop)	Acts as an adiabatic two-phase separator.
ADSORBER (RSTOIC)	P = 0 bar (no pressure drop) T = 40 °C CaO (solid) + $CO_2 \rightarrow CaCO_3$ (solid)	Presents simple modelling of chemical adsorption of CO_2 on CaO to form carbonate, assuming complete conversion with an excess of sorbent going into the reactor.
DUPLICAT (DUPLICATE)	-	Duplicates a stream into its multiple copies.
ANALYSIS (SEPARATOR)	For H_2O + IMPU stream, split fraction = 1 for water, H_2S, HCl and NH_3 components, while the rest of the components are set to zero	Generates dry and contaminant free stream of syngas for comparison with results in the literature.

Table 3. Proximate and ultimate analyses of the biomass feedstocks.

%	Cassava Peel [82]	MSW [83]	Cow Dung [84]
Carbon	47.21	35.1	33.07
Hydrogen	7.44	4.7	4.87
Nitrogen	1.35	1.4	2.90
Oxygen	43.70	16.1	58.33
Sulphur	0.04	0.2	0.63
Moisture	7.29	45.8	7.75
Ash	1,92	42.6	25.3
Volatile	68.16	51.1	54.55
Fixed Carbon	22.63	6.3	12.40

3.3. Estimating the Vehicle Stock

The COPERT (computer program to calculate emissions from road transport) methodology is the EU standard vehicle emissions calculator, which is consistent with the 2006 IPCC guidelines for the calculation of greenhouse gases [13]. Tailpipe emissions from different vehicle categories, including four-wheeled passenger vehicles, light commercial vans and pickups and heavy-duty trucks, are measured using a standardized method. CO_2 and other pollutants in the tailpipes of vehicles (CO, NOx, CH_4, NMVOCs and N_2O) are measured using certain parameters. Parameters such as the stock of vehicles, the vehicle type, the vehicular mileage or activity rate (in km), the emissions factor (kg/amount of activity) and the fuel economy in L/100 km (km/L) are generally used to estimate tailpipe emissions from fossil fuel consumption.

In the absence of statistical data for the stock of vehicles in Nigeria, it is assumed that the stock of vehicles is the total number of vehicles registered in the road transport sector [85], for the year 2018. The number of vehicles was estimated to be 11,760,871, and with a population of 198,000,000 people, that implies 6 vehicles per 100 persons (a vehicle per person ratio of 0.06) [66].

3.4. Vehicle Fleet Composition

The vehicle composition was taken from the World Bank report on the analysis of four sectors of the Nigerian economy [67]. The report estimated the vehicle fleet composition in Nigeria using the COPERT methodology. The disaggregated vehicle fleet in Figure 1 was used to derive the vehicle composition and fuel consumed in the road transport sector, as shown in Table 4.

Table 4. Disaggregated vehicle composition and fuel type.

Vehicle Type	Fuel Technology	Fuel Technology (%)	Mileage (km) [67]	Fuel Economy (L/100 km) [85]
Car/Saloon	Gasoline	99	17,000	9.08
	Diesel	1		9.08
Motorcycle	Gasoline	100	7000	3.25
Minibus/Omnibus	Gasoline	85	30,000	25.64
	Diesel	15		
Van and Pickup	Diesel	25	30,000	13.15
	Gasoline	75		
Truck/Tanker	Diesel	100	33,500	28.57

3.5. Estimating the Amount of Gasoline Consumed

In the absence of historical data on fuel consumption by vehicles in the Nigerian road transport sector, the amount of gasoline consumed for the six cities in this study was estimated using Equation (7). The vehicle "stock" for each of the selected cities is represented as the number of vehicle owners (v), which is obtained from Table 1. The vehicle per population ratio of 6 cars per 100 persons was used to estimate the number of vehicle owners in the selected cities. Using the COPERT methodology, the fuel consumption was obtained from the estimates of the activity level and vehicle fleet composition. From Table 4, 99% of cars, 85% of buses and 100% of motorcycles consumed gasoline. The NNPC estimated the daily consumption of gasoline in the country to be 75.1 million L in December 2020, which amounts to 27.3 billion L per year [63–65].

$$Fuel\ consumption = stock \times annual\ mileage \times fuel\ economy \quad (5)$$

3.6. Estimating the Amount of Diesel Consumed

Table 4 shows that 100% of heavy-duty trucks, 25% of vans and 50% of cars were the major contributors to diesel consumption. Similarly, by applying Equation (7), the amount of diesel consumed annually was obtained. According to the end of year report from the Nigeria National Petroleum Corporation, the daily consumption of diesel was 380 thousand L in December 2020, which amounts to 137 million L per year [63,64].

3.7. Calculating the CO_2 Emissions

CO_2 emissions regulations in Nigeria are applied under Euro 2 and Euro 3 emissions standards [67]. Euro 2 standards came into effect with the national policy on emissions in 2011; however, Euro 3 standards are yet to be implemented [85]. Nigeria imports most of its vehicles from western countries such as the United States and Europe [67]. The implication is that the estimation of the CO_2 emissions from vehicles in Nigeria is carried out based on a harmonized methodology with emissions estimates from vehicles in the United States and Europe, utilized as stipulated under the IPCC guidelines. In the absence of a national methodology approach for estimating emissions in the road transport sector, the tailpipe CO_2 emissions are estimated from the total amount of fuel consumed. The emission factors for diesel and petrol are estimated from the methodology applied by USEPA (United States Environmental Protection Agency) [86]. CO_2 emissions factors (VEF) for gasoline and diesel consumption were 8887 g CO_2/gallon and 10,180 g CO_2/gallon, respectively. Applying Equation (8), the CO_2 emissions per km are obtained by dividing the estimated emissions factor by the fuel economy of the different vehicle types, as provided in Table 4.

$$D = \frac{\text{VEF}}{\text{Fuel economy}} \times \text{Stock of vehicles} \quad (6)$$

where D is the CO_2 emissions per km, VEF is the vehicle emissions factor for diesel and gasoline and the stock of vehicles is the number of registered vehicles in the year 2018 in Nigeria [85].

3.8. Estimating the Amount of Hydrogen Gas That Can Serve as a Substitute for an Equivalent Amount of Gasoline and Diesel Consumption in the Road Transport Sector

In the transport system, hydrogen can be used directly in HICE vehicles as an energy carrier and for the provision of electricity in FCEVs. The energy conversion pathway involves the transfer of heat energy to mechanical energy in internal combustion engines. Generally, the density of liquid hydrogen at normal boiling point and 1 atm is 70.8 kg/m^3 [87]. At this density, hydrogen can provide almost three times the amount of energy as 1 L of gasoline. The lower heating values for hydrogen and gasoline are 120 MJ/kg and 44 MJ/kg, respectively. This also equates to 1 kg of hydrogen giving an amount of energy equivalent to 1 US gallon of gasoline (2.84 kg) [88]. However, when hydrogen is combusted in internal combustion engines or used as an energy carrier in fuel cell vehicles, it must be compressed and stored at about 700 bar, to increase its energy and storage density [89]. At 700 bar, it has a density of 42 kg/m^3 and is capable of replacing an equivalent amount of gasoline and diesel. This study adopts the density of compressed hydrogen when carrying out the analysis for fuel substitution. The amount of hydrogen available to serve as a substitute for diesel fuel and gasoline is determined from the lower heating value of diesel and gasoline with respect to hydrogen gas and is represented in the following equations:

$$V_{\text{diesel}} = \frac{V_{H_2} \times LHV_{H_2} \times n_{hce} \times \rho_{H_2}}{LHV_{diesel} \times n_{de} \times \rho_{diesel}} \quad (7)$$

$$V_{gasoline} = \frac{V_{H_2} \times LHV_{H_2} \times n_{hce} \times \rho_{H_2}}{LHV_{gasoline} \times n_{ge} \times \rho_{gasoline}} \quad (8)$$

where n_{hce} is the efficiency of hydrogen in an internal combustion engine [90] and n_{de}, n_{ge} are the efficiencies of diesel and gasoline in combustion engines, which are 40%, 35% and 30%, respectively [26,89–91]. The lower heating values and densities of hydrogen, diesel and gasoline, LHV_{H_2}, LHV_{diesel}, $LHV_{gasoline}$ ρ_{H_2}, ρ_{diesel} and $\rho_{gasoline}$ are taken as 120 MJ per kg, 42.5 MJ per kg, 44.5 MJ per kg, 0.042 kg per L, 0.83 kg per L and 0.75 kg per L, respectively [92,93].

3.9. Calculating the Amount of Avoided CO_2 Emissions

When utilized, hydrogen releases no harmful emissions; therefore, the amount of CO_2 emissions per year that could be avoided by using hydrogen in combustion engines rather than diesel or gasoline fuels is given in Equation (9).

$$CO_{2_{avoided}} = V_f \times VEF \quad (9)$$

where V_f is the volume of gasoline or diesel and value of the vehicular emission factor (VEF) is taken as 8887 g CO_2/gallon and 10,180 g CO_2/gallon for gasoline and diesel, respectively [13].

4. Results and Discussion

The results of the road sector analysis, the process of biomass gasification and the environmental analysis of CO_2 emissions are discussed in this section.

4.1. The Estimated Flow Rates Used in the Aspen Plus Model

With a feed ratio of 33.3%, the estimated flow rates for the mixed blend of cassava peel, cow dung and food waste from MSW are shown in Table 5.

Table 5. Estimated flow rates of biomass feedstock.

Selected City	Food Waste (Metric Tons/Year)	Cassava Peel (Metric Tons/Year)	Cow Dung (Metric Tons/Year)
Abuja	30,604	555,000	1,264,280
Enugu	53,844	555,000	175,594
Port-Harcourt	39,260	555,000	175,594
Lagos	147,034	555,000	175,594
Kaduna	117,519	555,000	1,264,280
Bauchi	35,139	555,000	1,264,280

4.2. Validating the Results of the Aspen Plus Model

Previous studies [45,50,80] did not include the upgrading of syngas by the water-gas shift reaction in their results. Hence, the model was validated for the syngas content before the shift conversion. The feedstocks used were refuse-derived fuel (RDF) and wood chips, as in the previous studies. A summary is given in Table 6. The heating values for syngas were calculated from the composition and gas component heating values available online [93].

Table 6. The validation of the simulation model using RDF and wood chips as feedstock.

	Feedstock: RDF; ER= 0.1 STBR = 0.4		Feedstock: Wood Chips; No Air Introduced STBR = 0.75	
Syngas Composition (vol % Dry and NH_3, H_2S and HCl Free)	**Literature [45]**	**Model (This Study)**	**Literature [50,80]**	**Model (This Study)**
H_2	42.4	43.9	45.8	42.44
CO	33.8	23.42	20.79	24.3
CO_2	13.5	18.99	20.19	19.80
CH_4	10.3	13.68	11.22	13.5
Syngas LHV (dry at 0 °C and 1 atm)	16.2 MJ/kg	15.6 MJ/kg	11.6 MJ/m^3	11.85 MJ/m^3 at 15.6 °C (15.3 MJ/kg)
CGE (LHV and mass basis)	83.3	80.0	75.3	80.12

4.3. Sensitivity Analysis

The effect of the operating parameters on the amount of hydrogen produced in the gasification process is examined in this section. The three main parameters were the gasifier temperature, the steam to biomass ratio and the equivalence ratio. The influence of the selected variables on the amount of CO_2 reduction in the road transport sector was also determined. A change in these parameters resulted in the production of different volumes of hydrogen, which consequently affects the amount of CO_2 released from the displacement of an equivalent amount of diesel and gasoline. In this study, a sensitivity analysis was carried out on the results for the location with the highest amount of hydrogen production, to examine the effect of the operating parameters. Kaduna had the highest amount of hydrogen production, and it represents the results that can be obtained from the other locations. Figure 4, shows the production potential of the six different locations. The positive correlation between the volume of hydrogen produced and the volume of diesel and gasoline displaced is shown in Figure 5, for a gasification temperature range of 750 °C to 900 °C.

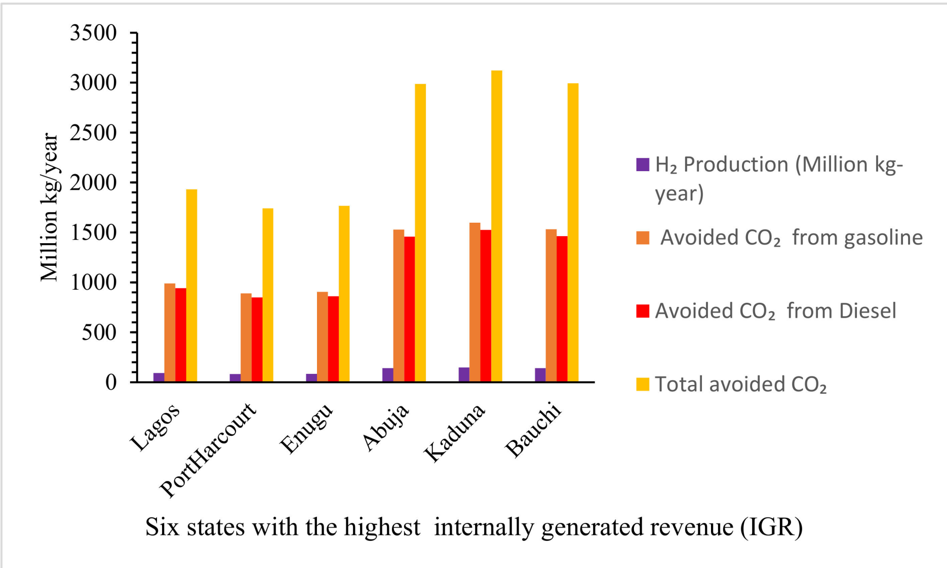

Figure 4. Results for six cities with the highest internally generated revenue (IGR).

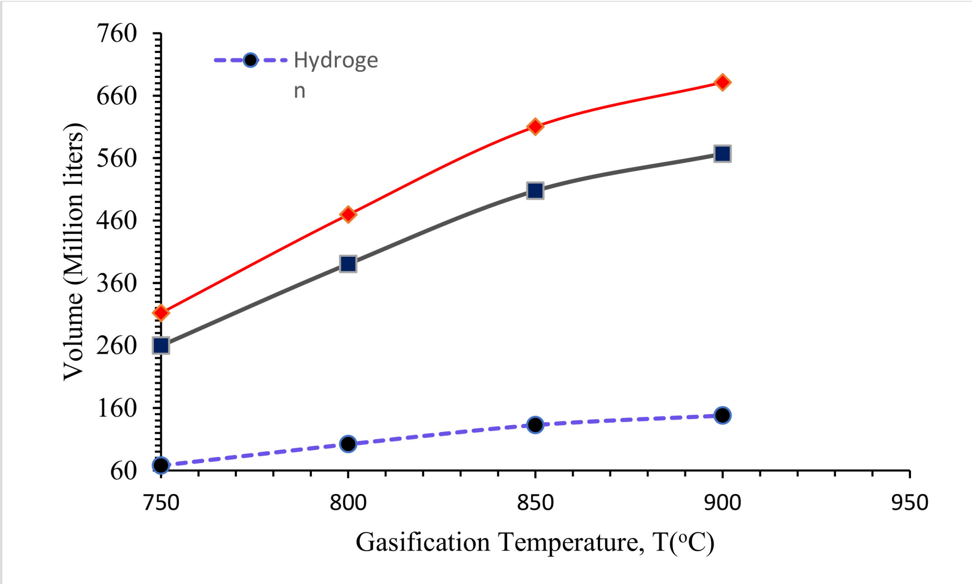

Figure 5. Effect of gasification temperature on hydrogen production and the diesel and gasoline displaced.

4.3.1. The Equivalence Ratio

The volumetric composition of hydrogen in the synthesis gas mixture was reduced by 6.1% when the equivalence ratio was varied from 0.1 to 0.4, as shown in Figure 6, while the CO_2 composition in the syngas increased significantly by 20.8%. The increase in equivalence ratio improved the conversion of the combustible syngas products (CO, H_2 and CH_4) to CO_2, thereby reducing their amounts in the reactions. The increase in equivalence ratio reduced the amount of CO_2 emissions that could be avoided, due to a reduction in the volume of hydrogen produced from the location. The production flow rate of hydrogen was reduced from 148 million kg to 129 million kg, as shown in Figure 7. The percentage reduction in the amount of avoided CO_2 emissions was about 12.5%.

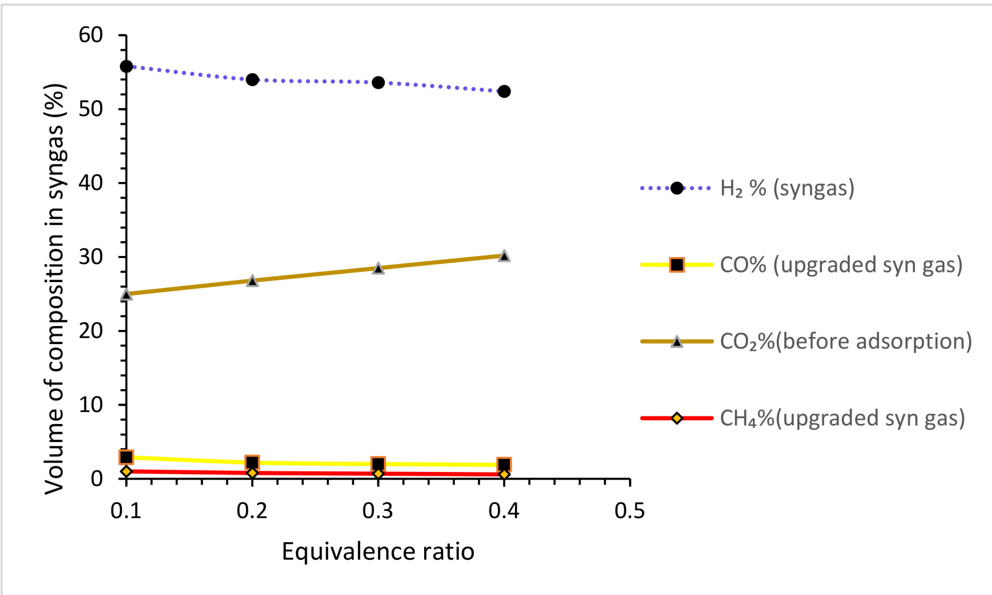

Figure 6. Effect of equivalence ratio on syngas composition.

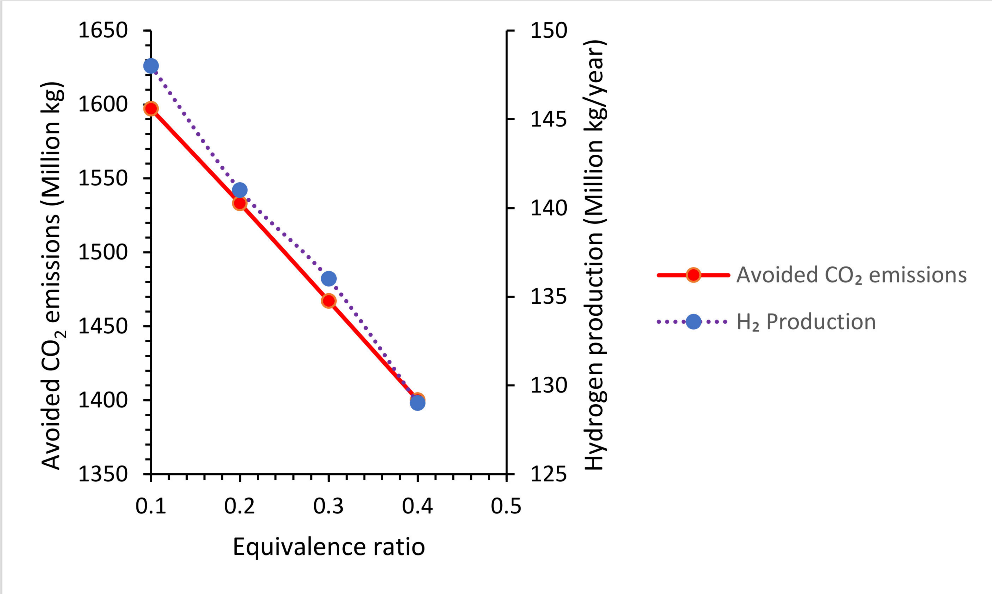

Figure 7. Effect of equivalence ratio on CO_2 avoided and hydrogen production.

4.3.2. Gasification Temperature

The maximum hydrogen yield was obtained at 900 °C. At temperatures above 950, the gasification process runs the risk of accumulating ash, which can disrupt the operation. Figure 8 shows that by varying the gasification temperature from 750 °C to 900 °C, the amount of H_2 was increased from 74.1% to 95%, and the amount of CO increased from 0.4% to 2.4%, while the amount of CH_4 and CO_2 decreased. This is as a result of the high temperature, which favors endothermic reactions in the gasifier. The high temperature favors the methane steam reforming reaction (see Equations (10) and (11)) and the Boudouard reaction (see Equation (12)). A high temperature also reduces the content of tar in the reaction [94,95].

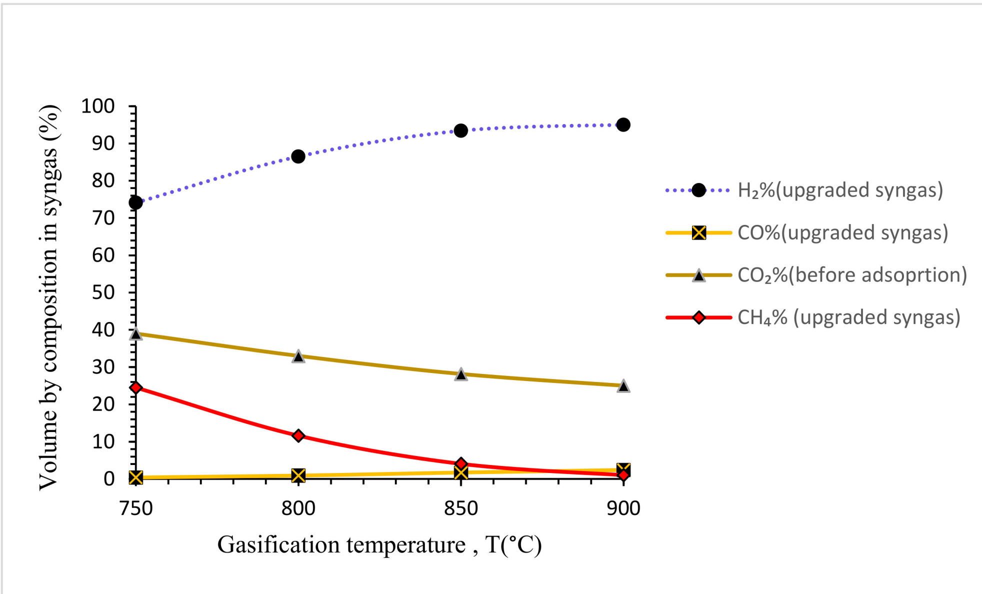

Figure 8. Evolution of syngas composition with gasification temperature.

$$CH_4 + H_2O \rightarrow CO + 3H_2 = +206 \text{ kJ/mol} \quad (10)$$

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 = +165 \text{ kJ/mol} \quad (11)$$

$$CO_2 + C \rightarrow 2CO = +172 \text{ kJ/mol} \quad (12)$$

The gasification temperature is positively correlated with the amount of CO_2 emissions reduction (see Figure 9). The amount of CO_2 avoided by replacing diesel with the hydrogen produced in Kaduna increased from 0.69 billion kg to 1.5 billion kg.

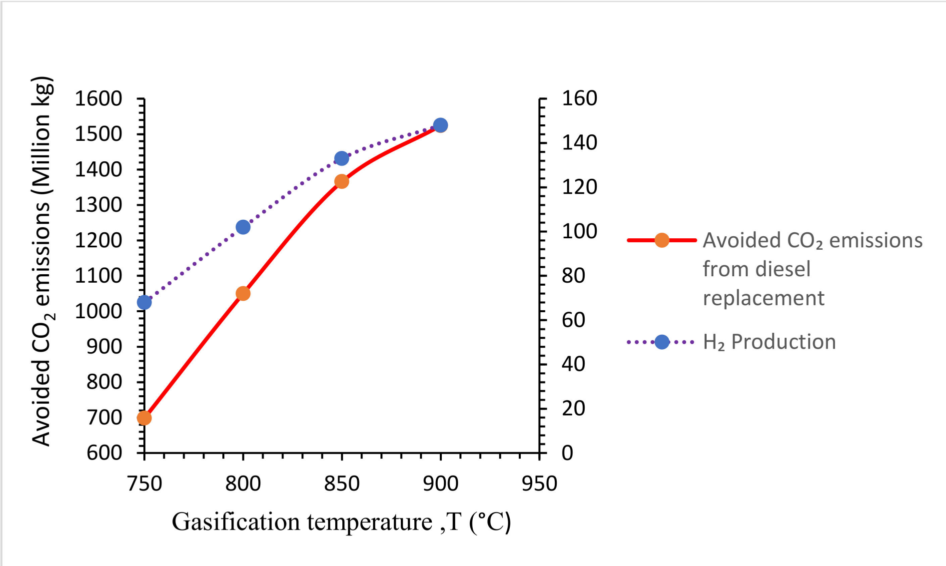

Figure 9. Effect of gasification temperature on the level of hydrogen production and the CO_2 emissions avoided.

4.3.3. Steam-to-Biomass Ratio

Varying the steam-to-biomass ratio from 0.4 to 0.8 resulted in a rise in the percentages of hydrogen and carbon dioxide, as shown in Figure 10, while the concentration of carbon monoxide declined. This is because, at higher steam-to-biomass ratios, the water–gas shift reaction is supported, with the thermodynamic equilibrium shifting to the right to favor the production of more hydrogen and carbon dioxide. The water–gas shift reaction is an exothermic process: $CO + H_2O \rightarrow CO_2 + H_2$—41 kJ/mol. At very high steam-to-biomass ratios, the activity of the water–gas shift reaction is impeded, which consequently reduces the quality of the hydrogen in the syngas.

The steam-to-biomass ratio showed a positive correlation with the amount of CO_2 emissions reduction, as shown in Figure 11. The amount of avoided CO_2 emissions increased by 13.6%, from 1.4 billion kg to 1.59 billion kg, as a result of the production of a greater volume of hydrogen. The volume of hydrogen produced increased from 2.94 to 3.34 billion L as the steam-to-biomass ratio varied from 0.4 to 0.8. The amount of energy in 3.34 billion L of hydrogen is equivalent to that in 681 million L of gasoline, considering the losses due to the different fuel conversion efficiencies and the use of the density of compressed hydrogen. Ideally, 3.7 L of hydrogen is required to give the equivalent energy to that in 1 L of gasoline. At a gasoline price of NGN 165.77 per L, the total savings in the cost of gasoline was about NGN 112 trillion.

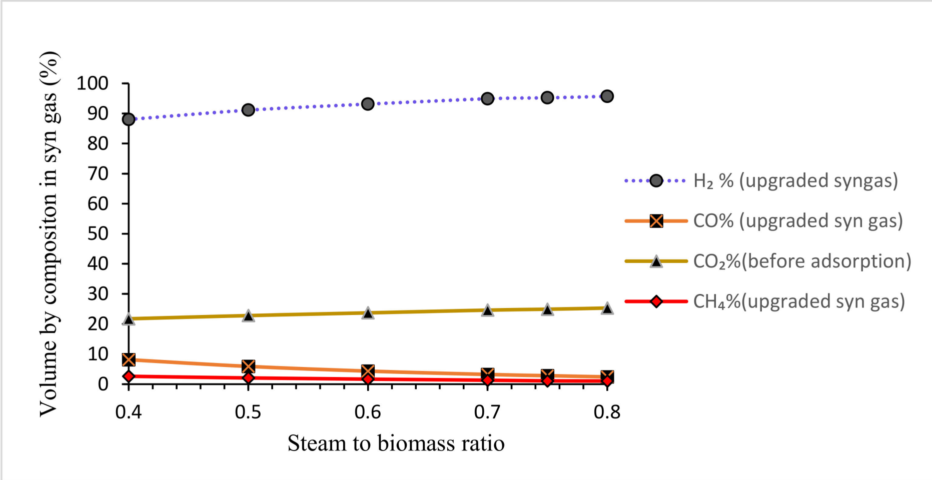

Figure 10. Effect of STBR on syngas composition.

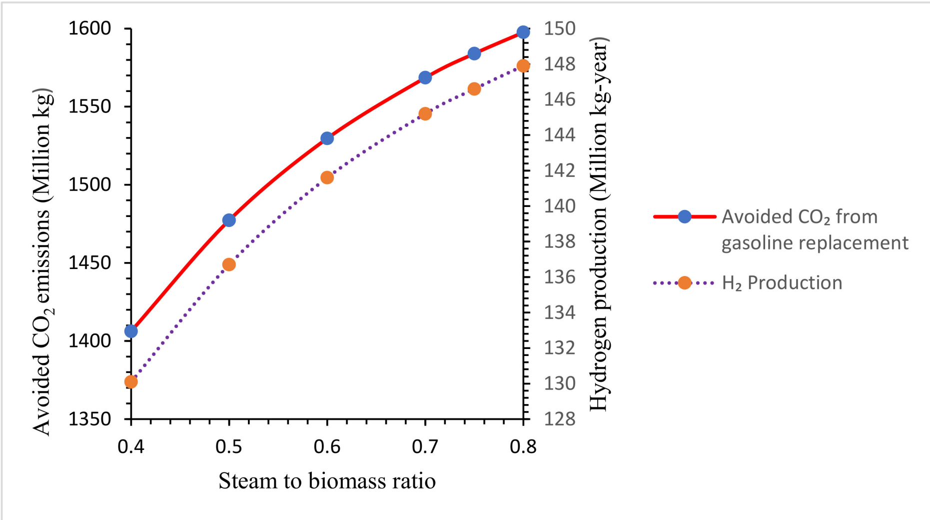

Figure 11. Effect of SBTR on CO_2 avoided and hydrogen production.

4.4. Technical Assessment of the Hydrogen Production Sites/Cities

A gasifier temperature of 900 °C, equivalence ratio of 0.1 and steam-to-biomass ratio of 0.8 provided optimum conditions for the gasification process. The molar composition by volume of the syngas and the hydrogen produced in tonnes per year is shown in Table 7. The total amount of hydrogen produced from the locations was 0.68 million tonnes, representing 0.971% of the global hydrogen produced in 2019, which was estimated to be 70 million tonnes [27].

Table 7. Results of the Aspen Plus simulations for the selected cities.

Selected City	Methane Content in Syngas (%)	H_2 Content in Syngas (%)	CO Content in Syngas (%)	Hydrogen Gas Produced (Tonnes/Year)
Abuja	1.1	96	2.6	141,511
Enugu	2.7	91	5.5	83,677
Port-Harcourt	2.8	91	5.7	82,433
Lagos	2.4	92	4.7	91,458
Kaduna	1.0	95	2.4	147,918
Bauchi	1.1	95	2.6	141,841

4.5. Environmental Assessment of the Hydrogen Production Sites/Cities

The amount of diesel and gasoline consumption was determined using Equation (5). Tables 8 and 9 show the amount of gasoline and diesel consumed in each of the selected cities. Lagos had the highest fuel consumption of 0.67 billion and 38.75 million L of gasoline and diesel, while Abuja had the lowest, at 0.1 billion L and 5.98, respectively.

Table 8. Gasoline consumption from the disaggregated vehicle composition.

Selected City	Gasoline Consumption (Billion L)	Cars/Saloons (N)	Motorcycles (N)	Vans (N)	Minibuses/Omnibuses (N)
Abuja	0.10	4510	32,062	1687	3585
Enugu	0.24	104,819	74,506	3921	8332
Port Harcourt	0.38	166,754	118,530	6238	13,256
Lagos	0.67	292,328	207,790	10,936	23,240
Kaduna	0.46	196,097	139,387	7336	15,589
Bauchi	0.34	149,251	106,089	5583	11,865

Table 9. Diesel consumption from the disaggregated vehicle composition.

Selected City	Diesel Consumption (Million L)	Cars/Saloons (N)	Mini/Omnibuses (N)	Heavy Trucks (N)	Vans (N)
Abuja	5.98	456	632	843	422
Enugu	13.89	1059	1470	1961	980
Port Harcourt	22.10	1684	2339	3119	1559
Lagos	38.75	2952	4101	5468	2734
Kaduna	26.00	1980	2751	3668	1834
Bauchi	19.78	1507	2093	2791	1396

4.5.1. Amount of CO_2 Emitted in the Transport Sector

The amount of CO_2 released from vehicular activity was obtained using Equation (6). The third and fourth columns of Table 10 show the amount of CO_2 emissions released in the selected cities. A total of 0.27 billion kg and 1.67 billion kg of CO_2 was released from gasoline and diesel consumption in Lagos, making this the city with the highest emissions. Abuja was the city with the lowest emissions. The total CO_2 emissions were 6.35 billion kg (6.35 million metric tons). This represents 0.086% of the global transportation sector's CO_2 emissions, which is 7.3 billion metric tons.

Table 10. CO_2 emissions from gasoline and diesel.

Selected City	Stock of Vehicles (N)	CO_2 Emissions from Diesel (Billion kg)	CO_2 Emissions from Gasoline (Billion kg)
Abuja	84,374	0.04	0.26
Enugu	196,070	0.09	0.59
Port-Harcourt	311,922	0.15	0.94
Lagos	546,816	0.27	1.67
Kaduna	366,810	0.18	1.11
Bauchi	279,183	0.14	0.84

4.5.2. The Amount of Avoided CO_2 Emissions

Hydrogen can serve as a replacement for diesel and gasoline consumption in vehicles for transportation purposes. Using Equations (7)–(9), the amount of diesel and gasoline that can be replaced was obtained, and the results are presented in Tables 11 and 12.

The replacement contributes to a total reduction in CO_2 emissions and cost savings in the purchase of gasoline and diesel. The total amount of diesel replaced in Lagos from Table 12 was 0.35 billion L, saving about NGN 101.5 billion. In addition, a total of 0.42 billion L of gasoline (see Table 11) could be replaced by 2.07 billion L of hydrogen produced in Lagos. This led to a cost saving of about NGN 70 billion. The prices for diesel and gasoline were taken as NGN 289.37 and 165.77 per L, according to the National Bureau of Statistics [66].

Table 11. Avoided CO_2 emissions from replacing gasoline consumption with the equivalent volume of hydrogen.

Selected City	Volume of Hydrogen Gas Produced (Billion L)	Volume of Gasoline Replaced (Billion L)	Avoided CO_2 Emissions from Replacing Gasoline Consumption (Billion kg)
Abuja	3.20	0.65	1.52
Enugu	1.89	0.38	0.90
Port Harcourt	1.86	0.37	0.89
Lagos	2.07	0.42	0.98
Kaduna	3.34	0.68	1.59
Bauchi	3.21	0.65	1.53

Table 12. Avoided CO_2 emissions from the replacement of diesel consumption with the equivalent volume of hydrogen.

Selected City	Volume of Hydrogen Gas Produced (Billion L)	Volume of Diesel Replaced (Billion L)	Avoided CO_2 Emissions from Replacing Diesel Consumption (Billion kg)
Abuja	3.20	0.54	1.45
Enugu	1.89	0.32	0.86
Port Harcourt	1.86	0.32	0.85
Lagos	2.07	0.35	0.94
Kaduna	3.34	0.56	1.52
Bauchi	3.21	0.54	1.46

4.6. Managerial Implication of Research

The aim of this study was to provide valuable insight into the effective utilization of biomass waste for the purpose of providing a source of energy for road transport users. The study proposed a gasification model with a post-treatment water–gas shift reaction and a CO_2 absorption process for obtaining hydrogen. The production of hydrogen was maximized at 900 °C and 0.8 for the gasification temperature and steam-to-biomass ratio. The maximum amount of hydrogen obtained was 147,918 tonnes per year from the Kaduna site. The key research findings are shown with respect to the fuel consumption preference for different categories of road users. The price variable is an essential driver of fuel consumption, influencing the aspect of buying behavior. The gasoline price in Nigeria is 170 NGN/L, which is equivalent to 0.376 USD/L. For an average four-wheeled car with moderate fuel economy, it is expected that 5 L of gasoline is consumed for every 100 km, which amounts to 11.2 USD/100 km. On the other hand, hydrogen gas is sold at an average cost of 3 to 6 USD/kg, and 6.1 kg of hydrogen is required per 100 km, which translates to an average cost of 24.4 USD/100 km. In comparison to gasoline, hydrogen is much more expensive for road users, and the implication is that unless the government invests in developing the infrastructures needed to drive down the cost of hydrogen, the consumption of gasoline will continue to grow. The findings are similar to those in other African countries. The cost of hydrogen will continue to remain higher than gasoline or diesel until there is enough evidence of financial, technical and political commitment from their respective governments. This is an insight for policymakers and hydrogen technology developers into the way forward for the development of a regional market that facilitates the logistics and proliferation of hydrogen technology.

5. Conclusions

The hydrogen generating potentials of cities with the highest internally generated revenues and vehicle ownership in the six geopolitical zones of Nigeria were examined. The results obtained revealed that the annual production of H_2 gas from these locations was estimated to be 0.688 million metric tons. When the produced hydrogen gas is compressed and stored under high pressures of around 700 bar, it can be used as an energy carrier in vehicles, providing an equivalent amount of energy by replacing diesel and gasoline consumption by volume. A total of 15.5 billion L of hydrogen gas produced was used to displace 3.172 billion L of gasoline and 2.639 billion L of diesel, respectively, in these locations. The overall impact on the environment from the substitution of hydrogen gas for gasoline and diesel consumption was the avoidance of 7.4 million tonnes and 7.09 million tonnes of CO_2 emissions. From an economical perspective, the savings from gasoline fuel expenses was NGN 525.6 billion. This is a huge reduction from the total gasoline consumption cost, recorded as NGN 3062 trillion, obtained from the nationwide consumption of 18.17 billion L in 2021. These savings could be used to cover other capital expenditures in the country. The sensitivity analysis revealed that varying the optimum condition for the steam-to-carbon ratio from 0.4 to 0.8 and the gasification temperature from 750 °C to 900 °C increased the amount of hydrogen available to achieve the reduction in CO_2 emissions from vehicle activity in the road transport sector. The advancement of hydrogen technology enables its application in the industrial, electricity and transport sectors. In the industrial sector, hydrogen can be used in the production of ammonia, which is an essential feedstock for manufacturing fertilizers. It can also be used in methanol and steel production. Its applications also extend to the provision of electricity to the grid or off-grid applications using fuel cells.

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