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Experimental investigation of heating values and chemical compositions of selected fuel woods as bio-fuel sources in developing countries

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Highlights

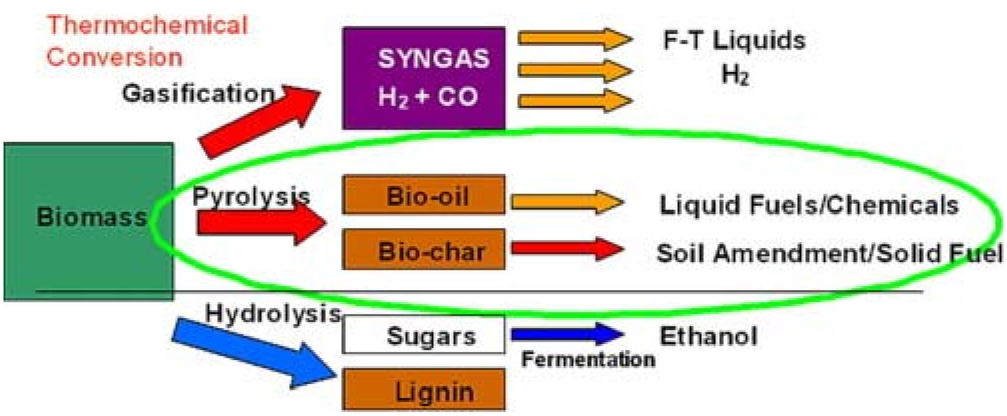
- The energy potential and heating properties of five selected indigenous fuelwood sawdust were investigated.
- Higher Heating Values (HHVs) of the selected sawdust samples were experimentally investigated using Bomb Calorimeter.
- HHVs were numerically calculated as a function of the ash content (AC), fixed carbon content (FCC), and volatile matter content (VMC).
- Comparative analysis of the experiment results and numerical of HHVs was carried out and.
- The GC and GC–MS analyses of bio-oils from the selected sawdust samples were carried out.

Abstract

Agro-waste disposal is a serious environmental problem in developing countries like Nigeria since there are insufficient waste management systems in place. However, it is possible to produce sustainable energy from these biomass wastes, which will lessen environmental damage. The heating value of biomass determines its energy content. The aim of this study was to determine experimentally the higher heating value (HHV) of five selected indigenous fuelwood sawdust and to assess the chemical composition of the pyrolysis yield products using a gas chromatography-mass spectrometry (GC–MS) analyzer. Results of the experimental analysis show that the HHVs of the selected fuel woods: *Adansonia digitata (Ad), Terminalia ivorensis (Ti), Khaya ivorensis (Ki), Mansonia altissima (Ma), Okoubaka aubrevillei (Oa) are* respectively, 21.02, 20.78, 20.75, 19.95, 19.80 and 20.46 MJ kg^{-1}. According to ultimate analysis-based correlation equation, the HHVs were found to be 18.56, 18.48, 18.42, 18.39 and 18.36 MJ kg^{-1} for Ad, Ti, Ki, Ma and Oa, respectively. While the proximate analysis-based correlation equation gave HHVs of 18.08, 18.12, 18.25, 18.16 and 18.37 MJ kg^{-1} for Ad, Ti, Ki, Ma

and Oa, respectively. The mean square error (MSE) was used to compare the deviation of the computed results from the experimental data. The statistical analysis indicates comparative agreement between the computed HHVs and the experimental data. The GC–MS analysis shows the presence of phenolic, ketone, fatty acid, ester, and alcohol compounds in the sawdust samples which is evidence that they have chemical and fuel compositions suitable for use as feedstocks in the pharmaceutical and dye industries as well as for the production of biodiesel for internal combustion engines. It can be inferred that the woody biomass residues can be useful sources of biofuels for developing nations' sustainable energy development if adequately processed with suitable technologies.

Graphical abstract.



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Introduction

Increasing interest in renewable biofuels has been fueled by rising energy prices, rising energy imports, fears about oil shortages, and greater awareness of the environmental impact of fossil fuels. To be a viable option, biofuels must provide net energy advantages, ecological benefits, economic competitiveness, and mass production without depleting the food supply. Biofuel manufacturing necessitates the use of energy to cultivate crops and convert them to biofuels [1]. One of the most promising energy sources for addressing the growing energy demand while protecting the environment and food crops is biomass waste. In many developing countries with sizable agricultural and forested areas, biomass waste makes about 40 to 50 percent of the energy supply [2]. Carbon, hydrogen, oxygen, nitrogen, and trace amounts of inorganic species produced from waste or animal manure make up the majority of biomass components. Every year, tons of wood wastes like shavings, chips, and sawdust are produced. Even while this massive volume of solid waste, primarily sawdust, has the potential to be an energy source, it frequently stresses the environment [3]. In addition to meeting SDG-7’s need for affordable and clean energy, harvesting usable energy from agricultural waste also has the potential to alleviate waste mismanagement problems, thereby tackling SDG-6, SDG-11 and SDG-13 in the process. To fully realize the promise of agrowaste-to-energy, however, concerted efforts would be needed to successfully link technology, economics, and political economy of livelihood through appropriate energy policy approaches [4].

As a practical substitute for fossil-derived fuels that can reduce energy costs, ensure energy security, and reduce global warming concerns, biofuels are gaining popularity [5]. Biofuels are divided into four groups based on the feedstock: first, second, third, and fourth generation biofuels. The first generation of biofuels is made up of plants that produce oil, sugar, and starch. The growth of genetically modified yields has accelerated in the two decades since their introduction. A few countries already produce first-generation fuels in significant commercial volumes. Non-edible lignocellulosic biomass, such as non-edible food crop residues (such rice husks or maize stalks) or non-edible whole plant biomass (e.g. agricultural waste or residues, forestry, grasses or trees grown specifically for energy), is used to make second-generation biofuels. Due to its availability and sustainability, lignocellulosic biomass is most likely to become a crucial renewable resource for the manufacture of cost-effective biofuels and bioproducts. In addition to becoming a significant replacement for fossil fuels, the production of bioenergy from lignocellulose biomass now accounts for around 9 % of the world's energy supply [6]. No nation has yet begun to market second-generation fuels. Third generation biofuels made from algae are gaining attention because they can be produced in large quantities, absorb CO_2, and require little effort to refine. The fourth generation of biofuels, a recent development with rapid expansion, uses engineered cyanobacterial development [7].

Due to its nontoxic, sulfur-free, biodegradable nature and renewable source, biofuels are being considered as replacement for fossil-derived fuels. Biofuels can replace fossil-derived fuels in the transportation, industry, and household (cooking) sectors due to their chemical composition, thermophysical qualities, and increased heat value (HHV). The utilization of various biofuels to replace petroleum-based fuels is depicted in Fig. 1. In spark-ignition engines, alcohol fuels can be used instead of gasoline, whereas compression-ignition engines can use biodiesel, green diesel, and DME. Fig. 2 depicts the use of biofuels for cooking, particularly in developing countries rural areas. In all cases, cooking with biofuels releases less (or significantly fewer) pollutants than cooking with solid fuels. Over 4.5 billion people cook with solid fuels in underdeveloped nations, and the accompanying indoor air pollution has serious health consequences [1], [2]. As a result, biofuels can improve the health of billions of people in underdeveloped nations.

The aforementioned issues call for full utilization of alternative energy sources. Woody biomass is one of the most significant renewable energy sources, and it can be converted into bioenergy [8]. Wood waste is all over Sub-Saharan Africa, especially in Nigeria, and it pollutes the environment. These wood wastes can be converted into valuable goods and are found in sawmills and other wood-related businesses. However, it is possible to determine these wood wastes' higher heating value (or calorific value) in order to assess their conversion potential to bio-oil, bio-char, pyroacids, and pyro-gas, which can be used in a variety of static applications like boilers, furnaces, engines, and turbines for the production of electricity [9]. According to studies, certain wood wastes can also be used to create a variety of compounds [10]. Food flavorings, resins, agrochemicals, fertilizers, and emission control substances fall under this category. A wide range of biomass feedstocks have been devised and developed into a variety of conversion processes. Pyrolysis is a technology included in this list. Char and ash are produced during the pyrolysis process, along with liquids like tar (a mixture of heavy hydrocarbons) and gases like H_2, CO, CO_2, CH_4, and N_2. The world is paying a lot of attention to pyrolysis technology, which is still in its early stages of development [11]. The idea of employing pyrolysis to extract biofuels from biomass wastes has been the subject of numerous investigations. Mohammed et al. [11] investigated the pyrolysis of groundnut shells in a vertically fixed bed reactor and found that the product yields are suitable for usage as an energy source and as starting materials for chemical synthesis. On a fixed bench-scale reactor, Tinwala et al[9].'s investigation into the pyrolysis of wastes and agro-industrial biomass mixes. They discovered biochar production of 27.5–40 % and bio-oil yield of 20.5–47.5 %. Due to its low moisture level and high energy content, Guanqun and Fernando [9] suggested beetle-killed lodgepole pine (BKLP) as a feedstock for quick pyrolysis. Two dedicated bioenergy crops growing on reclaimed coal-mine soils in West Virginia were reported and their pyrolysis products were defined by Oginni et al. in their study [10]. The manufacture and analysis of pyrolysis oil (bio-oil) produced from certain hardwood chips (Mahogany, Swietenia macrophylla) were disclosed by Chukwuneke et al. [11]. The pyrolysis of wood chips from oak, beech, fir, cherry, walnut, and linden was studied by Kozani et al. [12] at equal mixing fractions between 240 and 650 °C in a fixed bed reactor. They discovered that increased heating rates and reaction temperatures promote higher pyrolytic gas yields while reducing yields of bio-oil and char. The quick pyrolysis of hazelnut cupula was studied by Keleş et al. [13] using a fixed-bed reactor while varying the pyrolysis temperature from 400 to 700 °C, the sweeping gas flow rate, and the particle size. According to the study, the highest oil output was achieved at 600 °C and gas flow rate of 200 mL/min for diameters ranging from 0.150 mm to 0.425 mm. In a batch reactor, the pyrolysis of beech wood at temperatures between 350 and 450 °Celsius was studied by Bajus [14]. The data study revealed an average of 44.3 percent liquids, 30.6 percent biochar, and 25.1 percent gas, with acetic acid, formic acid, furfural, and lactic acid being the most prevalent liquid products. Using a fixed-bed tube reactor, Demirbas [15] examined the effects of pyrolysis on hazelnut shell, olive husk, beech, and spruce wood samples at various temperatures (350 to 525 °C). High concentrations of 1-hydroxy-2-butanone, acetic acid, 2,6-dimethoxyphenol, 1-hydroxy-2-propanone, methanol, 4-methyl-2,6-dimethoxyphenol, and 2-cyclopentene-1-one were found in increasing percentages of bio-oil 45 wt% at 500 °C.

The prime objectives of this study are to: (i) determine experimentally the higher heating values (HHVs) of five selected fuel woods (Adansonia digitata, Terminalia ivorensis, Khaya ivorensis, Mansonia altissima, Okoubaka aubrevillei) obtained from South Western Nigeria for effective utilization as bio-fuel and (ii) investigate the chemical composition of the pyrolysis products (bio oils) of the selected fuel wood samples using a gas chromatography-mass spectrometry (GC–MS) analyzer as potential substitute for fossil fuel..

In this study, pyrolysis method is used considering its superior ability to decompose biomass at temperatures between 300 °C and 600 °C and in the absence of an oxygen-rich atmosphere. Moreover, it is one of the best and most effective processes for degrading biomass. Three distinct products, including bio-oil, biochar, and biogas, can be produced by pyrolysis. Biomass co-pyrolysis is a low-cost and simple to operate method that has the potential to improve biofuel production.

The inconsistency of Nigeria's electrical supply can be attributed to a lack of diversification and increased energy demand. It is essential to add environmentally friendly green energy sources to the current hydroelectric and thermal power plants in order to offset the pollution caused by the burning of fossil fuels. Nigeria has made very little progress in the switch to renewable energy sources despite its massive population (more than 200 million) and strong agricultural production because of financial constraints and a dearth of systematic analyses of readily accessible biomass [16], [17], [18], [19]. In Nigeria, fuelwood, crop residues, agricultural crop wastes, animal wastes, energy crops, and other biomass energy resources are all readily available and, if fully developed, will inevitably contribute to the nation's sustainable energy development, increase national income, create job opportunities for both skilled and unskilled labors, and turn waste into wealth [20], [21], [22], [23], [24], [25].

Many developing nations are becoming more interested in biofuels as a way of effective utilization of biomass and expanding access to clean liquid fuels while lowering energy prices, ensuring energy security, and addressing concerns about global warming linked to petroleum fuels. Biomass technology, when used appropriately, provides a compelling foundation for utilizing specific types of biomasses to address both urban and rural energy needs [25], [26], [27]. Sustainable biomass energy deployment offers a lot of promise in Nigeria, especially in rural agricultural areas [28], [29].

Nigeria as a country in Sub-Saharan Africa has a land size of 923,768 square kilometers. Agricultural land covers around 74,500,000 ha of the country's total 91,077,000 ha [30]. In Nigerian mass land, forests, agriculture leftovers, urban and industrial waste products, and other biomass sources. Nearly 200 billion kg of biomass is produced each year. A study found that the biomass resources in Nigeria have the potential to provide up to 62 Mtoe (2.6 billion GJ) of energy. Given Nigeria's abundance of renewable energy resources and the low access of the populace to clean energy, the conversion of large amounts of biomass resources, primarily in the form of agricultural wastes and residues (animal, food, and municipal), to energy production could potentially increase energy supply while also improving the country's energy mix and balance. Furthermore, a stable power infrastructure would be in place, and rural areas with an abundance of agricultural waste biomass would have access to electricity [18].

Although bioenergy heat and power technologies exist, it is still important to increase the use of the most effective ones while also developing and deploying a number of new technology alternatives for Nigeria's effective and efficient biofuel production [30], [31].

According to Mckendry [32], the kind and quantity of biomass feedstock as well as the intended form of energy have an impact on the best biomass conversion technique. The development of biomass conversion systems varies throughout Nigeria; some are at the research stage, some are in the demonstration stage, and only a few are commercially successful. Biofuel production in Nigeria is still in its infancy, with biomass energy technologies like biogas, biofuels, improved woodstoves, and biomass briquetting available to a wide range of end-users [33]. The Nigerian Automotive Biofuel Program, which began in 2005, was a collaboration between the Federal Government, NNPC, Universities, R&D Institutes, commercial investors, and local farmers. The federal government required the NNPC to blend 10 % biofuel with fossil fuels at the country's refineries. Sugar and starchy crop biofuels are available in abundant for commercial or industrial usage in Nigeria, but their feedstocks are first-generation biomass, raising questions about sustainability [18].

Lack of (i) a comprehensive renewable energy strategy and the development of biofuel power technology (BPT), (ii) a supportive environment for the production and development of biofuels, and (iii) biomass technology development investors are the main obstacles preventing Nigeria from producing and developing biofuels on a commercial scale. In addition to the aforementioned factors, low levels of political and public awareness contribute to the poor opinions and attitudes that people have toward emerging renewable energy technology. Lack of skilled local labor, particularly in Nigeria's rural areas, to operate and maintain renewable energy equipment is a significant barrier to the broad adoption of bioenergy technology (BET). Additionally, there is a lack of institutional and financial infrastructure to facilitate the rapid uptake and development of BETs. The development of biofuel energy sources is hampered by the low costs of conventional energy sources (petrol, diesel, natural gas, etc.) [34].

Nigeria is not exempt from the benefits of biofuel because it provides developing nations with the chance to expand new sources of income, lessen their over-dependence on imported fossil fuels, and improve the environment. Therefore, the government at all levels must prepare to produce biofuel from her enormous biomass resources if Nigeria is to make a significant entry into the biofuels market, with every sector being placed in the usage of cleaner renewable energy. Through the cultivation of arable landmass for the supply of feedstock, this concept is anticipated to strengthen the Nigerian economy. Additionally, the following are crucial to overcoming the obstacles to large-scale biofuel production in Nigeria: (i) The government must put into effect a uniform policy that will serve as a foundation for other stakeholders, including as businesses, non-governmental organizations (NGO), research organizations, and private investors, to contribute their fair share to the development of the biofuel sectors; (ii) Steps that can be done to lower the cost of producing biofuel include localizing the feedstocks, choosing a less expensive way of harvesting, and selecting a less expensive method of transesterification, (iii) It is important to inform the public about the liberal and conservative aspects of using biofuels, particularly the advantages for the economy and environment. This will make it easier for people to accept using biofuel. (iv) In order to increase the output of biofuel production, technological improvement is needed in the fields of oil extraction, transesterification, and fermentation processes. (v) It is important to promote the mass production of non-edible feedstock for biofuel production, such as Jatropha curcas, Madhuca indica, and Pongamia pinnata. In Nigeria, this prevents biofuel feedstock from competing with food. (vi) The federal government must pique the interest of both the public and commercial sectors, particularly their cooperation in research and development [12], [18].

Section snippets

Samples preparation

The selected wood samples (Sample A (Adansonia digitata), Sample B (Terminalia ivorensis), Sample C (Khaya ivorensis), Sample D (Mansonia altissima), and Sample F (Okoubaka aubrevillei) for this investigation are generally used for furniture in Nigeria. The selected wood samples were obtained from sawmills in Ota metropolis in South Western Nigeria. The wood samples were processed into sawdust at the processing unit, Bells University of Technology, Ota, Nigeria. The samples of sawdust were

Results of experimental analysis of HHVs of fuel wood samples

Using an oxygen bomb calorimeter, an experimental assessment of the higher heating value of the selected fuel wood samples was made. Table 1 shows the findings of an experimental investigation of the higher heating values of the five fuel wood samples that were selected for this study. The average values of HHVs for each wood sample varies from 19.80 to 21.01 MJ/kg. Fuel wood sample - *Adansonia digitata* has the highest heating value of 21.01 MJ/kg while the fuel wood sample - *Okoubaka aubrevillei*

Conclusion

In this study, the heating values and chemical composition of five selected fuel wood samples have been investigated experimentally and analytically. The selected fuel wood samples are *Adansonia digitata, Terminalia ivorensis, Khaya ivorensis, Mansonia altissima and Okoubaka aubrevillei* collected from Ota, South–West, Nigeria. The proximate analysis shows that the Ash Content, Fixed Carbon Content and Volatile Matter obtained from the selected sawdust vary from: 1.08–1.93 %, 14.09–14.80 % and

CRediT authorship contribution statement

Joseph A. Oyebanji: . **Sunday O. Oyedepo:** Supervision. **Olawumi T. Oyebanji:** Investigation. **Araoyinbo O. Alaba:** . **Oluwaseun Kilanko:** . **Joseph O. Dirisu:** . **Bahaa Saleh:** .

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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  There has been increasing research on providing clean and efficient energy for household cooking. Renewable energy technologies are gaining significant attention and momentum as viable alternatives for household cooking, motivated by the urgent need to reduce dependence on traditional cooking fuels sourced from firewood, charcoal, and fossil fuels (Alfa et al., 2021; Oyebanji et al., 2023). These conventional fuel sources contribute to deforestation, air pollution, and greenhouse gas emissions, pose health risks due to indoor air pollution (Ukaogo et al., 2020; Nnodim et al., 2022; Onokwai et al., 2022a).
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  The conversion of biomass waste into energy shows high energy potential and is sustainable and environmentally friendly (Abdullah et al., 2010; Ibitoye et al., 2023; Kumar et al., 2023). Fuel with a

higher heating value (HHV) will produce more energy (Xu and Yuan 2015; Oyebanji et al., 2023). HHV measurements can be carried out experimentally using a bomb calorimeter.
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