

## **The potentials of waste-to-energy system in Nigeria: A study of pyrolysis conversion of wood residue to bio-oil in major cities of south-western Nigeria**

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### **ABSTRACT**

*In this study, the potentials of waste-to-energy system in Nigeria had been uncovered by considering the production of bio-oil from wood residue generated in major cities of south-western Nigeria using pyrolysis conversion. The major cities examined were Lagos, Abeokuta, Ibadan, Ilorin, Ado-Ekiti, Akure and Ile-Ife with wood residue generation of 807.7 Ton/day, 1,335.4 Ton/day, 65.5 Ton/day, 69.8 Ton/day, 15.1 Ton/day, 14.4 Ton/day and 8.1 Ton/day respectively. High tonnages generation from Abeokuta and Lagos result from their favourable environmental condition for afforestation, over-population and industrial influences. The potential of producing 1,161,242.4 litres/day of bio-oil using pyrolysis from a total of 2,316 Ton/day of wood residue generated from cities examined was discovered. The liable revenue to be generated from the sale of this bio-oil at ₦50/litre is ₦21.2 billion/year which can equally be used in providing lacking infrastructural facilities in examined cities. However, effective techno-economic analysis of the process is very important to know the capital and operating costs involved. Also, investigations into pyrolysis process optimization of wood residue are necessary to have optimum bio-oil production based on the available resources.*

**Keywords:** waste-to-energy system, bio-oil, pyrolysis conversion, wood residue, diesel, cities.

### **INTRODUCTION**

Waste-to-energy (WtE) refers to any waste treatment that creates energy in the form of electricity or heat from a waste source that would have been disposed in landfill [1]. The creation of energy from organic renewable materials in the form of gas, liquid or solid holds tremendous beneficial potential. Achieving solutions to possible shortage in fossil fuels and environmental problems that the world is facing today requires long-term potential actions for sustainable development. In this regard, renewable energy resources appear to be one of the most efficient and effective solutions [2]. The importance of alternative energy development has increased rapidly due to high international crude oil prices. The Nigerian government launched its Renewable Energy Master Plan (REMP) in January 2007 which provides a roadmap for the gradual move away from fossil fuels and an increase in the role of renewable energy in satisfying the country's energy needs [3]. Although the first facility that combusted municipal solid waste for energy came on line in New York City in 1898, the industry did not experience rapid growth until 1978 with the enactment of the Public Utility Regulatory Policy Act [4].

Bio-oil has been recognized as a representative renewable energy source and chemical feedstock [5] which can be produced by fast pyrolysis conversion of wood residue [6]. Bio-oils are produced by pyrolysis processes where the biomass feedstock is heated in the absence of air, forming a gaseous product, which then condenses. Slow pyrolysis produces large amounts of coke, which can be used as a solid fuel, whereas fast pyrolysis produces bio-oils in high yields of up to 80 wt % dry feed [7]. Bio-oil is an acidic, viscous, water-soluble liquid that has a dark-brown colour and a pungent smoky odour [8]. Figure 1 represents the diagram of a sampled bio-oil. Pyrolysis is an irreversible

thermochemical decomposition of organic material at elevated temperatures without the participation of oxygen involving simultaneous change of chemical composition and physical phase [9]. Pyrolysis dates back to ancient Egyptian times where tar for caulking boats and an embalming agent were made from pyrolysis. Since then, the process had been improved and is widely used in charcoal and coke production. In the 1980's, scientists found that the liquid yield of pyrolysis could be increased in fast pyrolysis, where the biomass is indirectly heated and condensed rapidly [10].



Figure 1: Boi-oil [12]

Wright *et al.* [11] developed techno-economic models for assessment of the conversion of biomass to valuable fuel products via fast pyrolysis and bio-oil upgrading. Themelis *et al.* [12] examined the recovery of energy from New York City solid wastes by pre-processing the combustible components of Municipal Solid Wastes (MSW) and using them as a fuel in a properly designed combustion reactor and thermoelectric plant to generate electricity and process steam. They concluded that energy recovery from MSW could reduce considerably the amount of land consigned annually to landfilling and also decrease to a small extent dependence on fossil fuels. The United States had very large sustainable supplies of wasted solids which could multiply its contribution to their national energy supply by a factor of 10 [9]. Many waste-to-energy companies had existed all over the world which include Agri-Therm (Canada), Ozmotech (Australia), Integrated Environmental Technologies (United States), Sustec Schwarze Pumpe (Germany), Waste Management (New Zealand), TAD Energia Ambiente (Italy), Batneec Dumfries (U.K.), AddPower (Sweden) and many more [13]. In 2007, there were more than 600 waste-to-energy (WtE) plants in 35 different countries. The United States processes 14 percent of its trash in WtE plants. Denmark processes (54 percent of its waste materials) more than any other country [1]. The potentials of waste-to-energy system had been discovered all around the globe.

Many researchers had examined energy generation from different waste sources using different conversion approaches. Ofoefule *et al.* [14] investigated biogas production from paper waste and its blend with cow dung in equal ratio. The two variants were subjected to anaerobic digestion in a 50L metal prototype biodigesters in the ratio of 3:1 of water to waste under a 45 day retention period and mesophilic temperature range of 26°C - 43°C. The physicochemical parameters of the wastes were determined including microbial analysis. Results obtained showed that paper waste had a cumulative gas yield of  $6.23 \pm 0.07 \text{ dm}^3/\text{kg}$  of slurry with the flash point on the 2nd day. An overview on gasification of biomass for production of hydrogen rich gas was examined by Aly [15]. Gasification was chosen as one of the more conventional methods for conversion of biomass due to some important reasons such as space consideration, flexibility of fuels used, reducing the volume of solid waste and recovery of energy. A study of the effect of blending of commercially available petrodiesel with biodiesels derived from NaOH-catalyzed homogeneous transesterification of methanol with groundnut and soyabean oils respectively had been done by Hamza *et al.* [16]. They concluded that the density, kinematic viscosity and flash point of petrodiesel/biodiesel blends increases with increase in the concentration of biodiesels in the blends and that the heating value of petrodiesel/biodiesel blends increases with decrease in the blend levels. Biogas production from blends of bambara nut (*Vigna subterranea*) chaff with some animal and plant wastes was studied by Ofoefule *et al.* [17].

### 1.1 Wood as a Major Raw Material of Bio-Oil

Wood and other forest biomass can be converted to pyro-gas and bio-oil during fast pyrolysis. The pyro-gas could be used in generating heat energy to power turbine for electricity generation while bio-oil may be used as substitute for diesel in many static applications, such as boilers, furnaces, engines and turbines for electricity generation ([18], [19]). Until AD 1850, wood was the main source of energy in the world [20]. About 13% of the world's primary energy was derived from forest biomass in 1987 while two billion people in the rural communities of the developing countries depend on biofuel for domestic cooking, steam raising, heat generation and crop ripping [21]. Wood residues produced during milling and re-sawing activities include tree barks, cut slabs, sawdust, plain shavings and

strips whose generation can be traced back to the 18th century [22]. About 20 to 50 percent of sawmill timbers end up as wood waste during processing [6]. Wood is a combustible carboxylic material that is made up of carbon, hydrogen and oxygen. The combustible characteristics of wood have made it a valuable source of heat energy [6].

### 1.2 Principle of Fast Pyrolysis Conversion

The wood residue feedstock preparation involves drying the low-grade wood chips to less than 10 wt % moisture to reduce the amount of water in the bio-oil [23] and then ground the dried wood chips to the correct size of less than 3mm [24] or 1 mm in diameter for fast heat transfer rates [25]. Dried and grounded feedstock is stored in a hopper near the pyrolysis reactor. A bubbling fluidized bed pyrolysis reactor is used to convert the prepared wood chips into three components which are small particles of solid char (aerosols), condensable gases and non-condensable gases [26]. Silica sand is used as the inert material inside the reactor as it can withstand temperatures up to 1,500°C and aid heat transfer. The bed is heated indirectly by flue gases in the jacket of the reactor to temperatures from 700°C to 1,000°C. Nitrogen gas is also added to the reactor to act as a fluidizing gas [24]. The three components from the pyrolysis reactor are then sent to a cyclone (cone-like apparatus) that uses centrifugal force to keep heavier particles against the wall. Gravity then pulls the solid particles (aerosols) downward to a collection tank, while the gases (condensable and non-condensable) come out of the top of the equipment. When the cleaned gases exit the cyclone unit, they must be cooled to form the bio-oil and non-condensable (recyclable) product gases. This prevents further reactions from taking place in the quencher. Table 1 shows the key fast Pyrolysis design features while the diagram of the system is shown in figure 2 below. The process of pyrolytic decomposition of dry and ash free biomass can be represented as [27]:

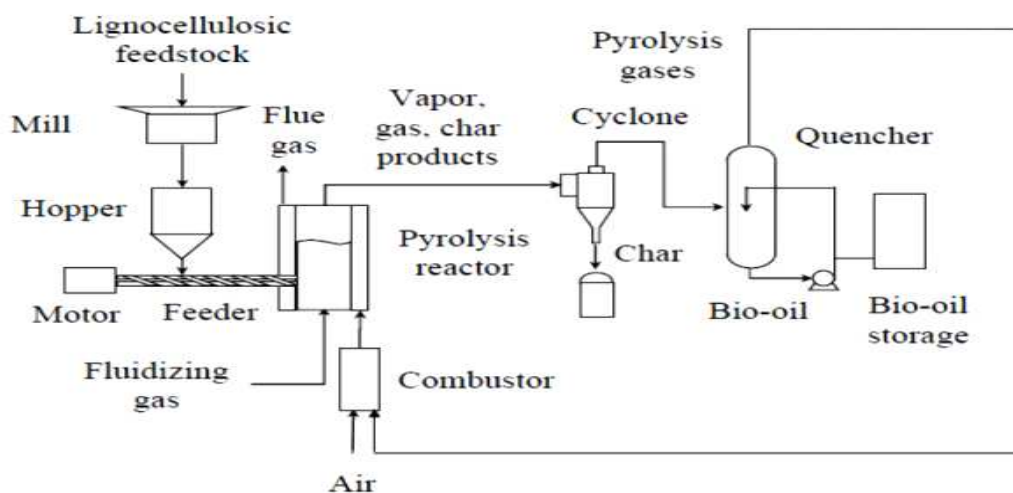
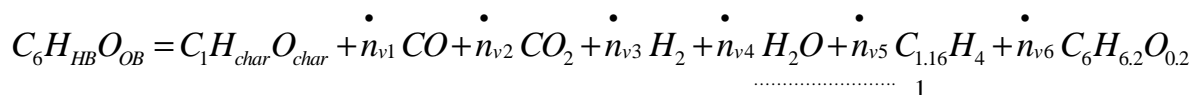


Figure 2: Fast Pyrolysis System [28]

### 1.3 Chemistry of Bio-Oil

Bio-oils are usually a dark brown, free-flowing liquid that has a distinctive odor. During bio-oil production, a large number of reactions occur. These include hydrolysis, dehydration, isomerization, dehydrogenation, aromatization, retro-condensation and coking. The exact composition of the bio-oil is dependent on the feedstock, organic nitrogen or protein content of the feedstock, heat transfer rate and final char temperature during pyrolysis, extent of vapor dilution in the reactor, time and temperature of vapours in the reactor, time and temperature of vapours in heated lines from the reactor to the quench zone. Others are efficiency of the char removal system, water content of the feedstock, storage condition and efficiency of the condensation equipment to recover the volatile components from the non-condensable gas stream [30].

The chemical composition of bio-oils reported by Milne *et. al.* [31] is shown in figure 3. Branca *et. al.* [32] reported that more than 400 organic compounds have been found in bio-oils. The compounds in the bio-oil can vary by more than an order of magnitude. The bio-oil contains acids (some of the major components include acetic, propanoic), esters (methyl formate, butyrolactone, angelica lactone), alcohols (methanol, ethylene glycol, ethanol), ketones (acetone), aldehydes (acetaldehyde, formaldehyde, ethanedial), miscellaneous oxygenates (glycolaldehyde, acetol), sugars (1,6-anhydroglucose, acetol), furans (furfurol, HMF, furfural), phenols (phenol, DiOH benzene, methyl phenol, dimethyl phenol), guaiacols (isoeugenol, eugenol, 4-methyl guaiacol) and syringols (2,6-DiOMe phenol, syringaldehyde, propyl syringol). The multicomponent mixtures are derived primarily from depolymerization and

fragmentation reactions of the three key building blocks of lignocellulose: cellulose, hemicellulose and lignin. The guaiacols and syringols are formed from the lignin fraction, whereas the miscellaneous oxygenates, sugars and furans are formed from the cellulose and hemicellulose biomass fraction. The esters, acids, alcohols, ketones, and aldehydes are probably formed from decomposition of the miscellaneous oxygenates, sugars and furans.

Table 1: Key Fast Pyrolysis Design Features [29]

Pretreatment	
particle size	small particles needed; expensive
feed drying	essential to ~10%
washing and additives	for chemical production
Reactor	
heat supply	high heat transfer rate needed
heat transfer	gas–solid and/or solid–solid
heating rates	wood conductivity limits heating rate
reaction temperature	500 °C maximizes liquids from wood
reactor configuration	many configurations have been developed
Product Conditioning and Collection	
vapor residence time	critical for chemicals, less for fuels
secondary cracking	reduces yields
char separation	difficult from vapor or liquid
ash separation	more difficult than char separation
liquids collection	difficult; quench and ep seem best

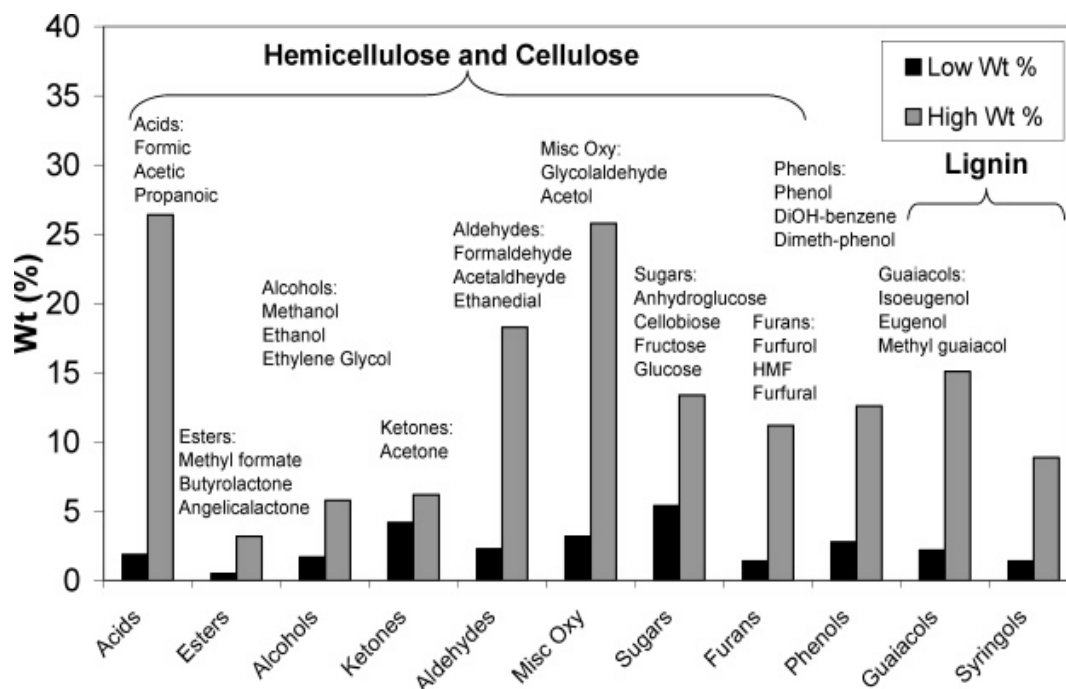


Figure 3: Chemical Composition of bio-oils [31]

#### 1.4 Problems of Bio-Oil Produced from Bio-mass

The most significant problems of bio-oils as a fuel are poor volatility, high viscosity, coking, corrosiveness and cold flow problems [7]. These problems have limited the applications of bio-oils. No quality standards have yet been made for bio-oil production. The main concerns for burning bio-oils in diesel engines have to do with difficult ignition (due to low heating value and high water content), corrosiveness (acids) and coking (thermally unstable

components). Bio-oils must be upgraded or blended to be used in diesel engines. Bio-oils polymerize and condense with time and this process is accelerated by increasing temperature, oxygen exposure and UV light exposure. These reactions result in increasing viscosity and phase separation in the bio-oil. A critical review by Diebold [30] on the chemical and physical mechanisms of the storage stability of fast pyrolysis bio-oils revealed that the probable reactions that occur within bio-oil that cause degradation are organic acids with alcohols forming esters and water, organic acids with olefins forming esters, aldehydes and water to form hydrates, aldehydes and alcohols forming hemi-acetals or acetals and water and organic sulfur forming oligomers. Other probable reactions include aldehydes forming oligomers and resins, aldehydes and phenols forming resins and water, aldehydes and proteins forming oligomers, unsaturated compounds forming polyolefins and lastly air oxidation that forms acids and reactive peroxides (which catalyze polymerization of unsaturated compounds).

### **1.5 Economics and Thermal Efficiencies of Bio-Oil Production Methods**

The major challenges for producing bio-oils are cost of bio-oil is 10-100% more than fossil fuel, availability (there are limited supplies for testing and development of applications), there are a lack of standards and inconsistent quality, bio-oils are incompatible with conventional fuels, users are unfamiliar with this material, dedicated fuel handling systems are needed and pyrolysis as a technology does not enjoy a good image [7]. The results of the economics and process thermal energy efficiency for production of liquid transportation fuels analyzed by the Working Group of the International Energy Agency using direct biomass liquefaction activity are shown in table 2.

The assessment was done with liquid fuels from atmospheric flash pyrolysis (AFP) and liquefaction in pressurized solvent (LIPS). Three steps analyzed included primary liquefaction to a crude oil product, catalytic hydrotreating to upgrade the crude product to a deoxygenated product oil and refining the deoxygenated product to gasoline and diesel fuel. The refining costs were estimated based on costs for refined oils derived by liquefaction of coal and oil shale and do not represent actual experimental results. The AFP process consisted of rapid pyrolysis in a sand bed of wood fibers to vapors and chars developed at University of Waterloo. The LIPS process was based on tests at the Biomass Liquefaction Experimental Facility in which wood chips were mixed with recycled wood derived oil, sodium carbonate and syn-gas in an upflow tubular reaction at 350°C, 20.5 MPa with a 20 min residence time. The economic analysis was based on a plant capacity of 1000 dry tons/day of biomass, a cost of \$30/metric ton of wood chips (50% moisture content) and a 10% interest rate. The capital cost for primary liquefaction of oils with LIPS was 70-80% higher than for AFP. The capital cost for the catalytic upgrading of the oils from the AFP process is higher than LIPS process since liquefaction-derived oils have a higher oxygen content than pyrolysis-derived oils. Therefore, the final capital cost for the AFP oils was only 14-22% that for the LIPS process. The process thermal energy efficiency of the primary oil products ranges from 0.61 to 0.68 for the pyrolysis oils to 0.48 - 0.55 for the liquefaction oils. The PTE decreases during catalytic upgrading and refining to 0.48- 0.52. It has been claimed that the HTU liquefaction process has an overall PTE of 70-90% [33].

### **1.6 Bio-Oil Mixtures**

Bio-oils from fast pyrolysis are not soluble in petroleum-derived fuel due to their high water content, however, blending of diesel with bio-oils can be accomplished using surfactants ([35],[36]). Bio-oil emulsions have promising ignition characteristics but also have a high cost due to surfactant addition and a high energy cost for emulsification. Higher corrosion levels occur in engine applications with the bio-oil - diesel emulsions [36]. Ikura et al. [35] produced emulsions of bio-oil obtained by fast pyrolysis of hardwood from 10 to 30 wt % bio-oil using a mixture of Hypermer B246SF, Hypermer 2234 surfactant and No. 2 diesel fuel. The cetane number, which is a measure of the diesel fuel quality with higher cetane numbers being better for engine use, decreased from 46, 43, 38, to 34 as the bio-oil concentration increased from 0, 10, 20, to 30 wt %, respectively. The corrosivity of the emulsions was about half that of the bio-oil, and the viscosity of the emulsion increased as the fraction of the bio-oil increased.

### **1.7 Geographical Location of the Area of Study**

In Nigeria, south-western region is one of the six geopolitical zones. It falls on latitude 6° to the North and latitude 4° to the south. It is marked by longitude 4° to the West and 6° to the East. It is bounded in the North by Kogi State, in the East by Edo and Delta States, in the South by Atlantic Ocean and in the West by Republic of Benin. This zone includes seven states including Lagos, Oyo, Ogun, Ondo, Kwara, Osun and Ekiti states where their common spoken language is "Yoruba". The maps of Nigeria and her south-western region are shown in figures 1.3 and 1.4 respectively.

**Table 2: Economic and Thermal Efficiency Analysis for Production of Gasoline and Diesel Fuels by Pyrolysis and Liquefaction [34]**

	atmospheric flash pyrolysis (AFP)		liquefaction in pressurized solvent (LIPS)	
	present	potential	present	potential
Total Capital Requirement (\$U.S. millions)				
primary liquefaction	49.8	26.4	84.2	48.4
crude upgrading	46.6	34.3	26.8	26.0
product finishing	14.5	0.7	15.3	0.7
total	110.9	61.4	126.3	75.1
Production Costs (\$U.S. million/year)				
fixed operating costs	14.48	10.77	14.48	10.03
variable operating costs	25.74	23.67	33.44	33.60
(feedstock costs)	(20.00)	(20.00)	(20.00)	(20.00)
capital charges	12.96	7.17	14.75	8.78
total production cost	53.18	41.61	62.67	52.39
Minimum Selling Price (\$U.S./GJ)				
bio-oil	9.32	6.91	13.44	12.27
refined bio-oil	16.24	12.99	19.54	14.77
Process Thermal Efficiency ( $\frac{\text{energy}_{\text{liquid products}}}{\text{energy}_{\text{feed+inputs}}}$ )				
primary product from liquefaction	0.61	0.68	0.55	0.48
finished product	0.52	0.53	0.48	0.49
Life Cycle Thermal Efficiency ( $\frac{\text{energy}_{\text{liquid products}}}{\text{energy}_{\text{feed+inputs}}}$ )				
finished product	0.40	0.40	0.36	0.37



**Figure 1.3: Map of Nigeria**



**Figure 1.4: Map of South-western Nigeria**

**2. Wood Residue Generated in the Area of Study**

A huge volume of wood residue is generated annually from timber processing activities around sawmills, plank markets and furniture making factories in cities within Nigeria. About 294,798 tons of wood waste is generated yearly (807.7 Tons/day) in the city of Lagos [37] while about 2,288m<sup>3</sup> is generated daily (1,335.4 Tons/day) in Abeokuta [38]. Lasode *et. al.* [39] revealed that 119.52m<sup>3</sup> of wood residue is generated daily (69.8 Tons/day) in Ilorin the capital of Kwara State, Nigeria. The amount of solid waste generated per person per day in some Nigeria cities are as follow: Ado-Ekiti in Ekiti state (0.71Kg/person/day), Akure in Ondo state (0.54Kg/person/day), Ile-Ife in Osun state (0.46Kg/person/day) and Ibadan in Oyo state (0.71Kg/person/day) [40]. However, the population of Ado-Ekiti, Akure, Ile-Ife and Ibadan according to 2006 census had been reported to be 308,621; 387,087; 256,449 and 1,338,659 respectively [41]. The total amount of solid waste generated per day (SW/day) in Ado-Ekiti, Akure, Ile-Ife and Ibadan is calculated thus:

$$SW/day = SW/person/day \times Population \dots\dots\dots 1$$

Thus, solid waste generated per day in Ado-Ekiti, Akure, Ile-Ife and Ibadan is 219,121 Kg; 209,027 Kg; 117,967 Kg and 950,448 Kg respectively. It had also been reported that the percent of wood residue composition in solid waste in Africa is 7% [42]. The amount of wood residue generated per day is calculated thus:

$$\text{Wood Residue} / \text{day} = 0.07 \times \text{SW} / \text{day} \quad \dots\dots\dots 2$$

This implies wood residue generated per day in Ado-Ekiti, Akure, Ile-Ife and Ibadan is 15,339 Kg (15.1 Tons); 14,632 Kg (14.4 Tons); 8,258 Kg (8.1 Tons) and 66,531 Kg (65.5 Tons) respectively using a conversion factor of

$$1\text{Kg} = 9.842 \times 10^{-4} \text{Tons} \quad \dots\dots\dots 3$$

The total amount of wood residue generated on daily basis from areas of study is tabulated in table 3.1 below.

### 3. The Potentials of Bio-Oil Production from Wood Residue by Pyrolysis

It has been estimated that a commercial bio-oil production pyrolysis plant processing 100 tonnes of wood residue per day would produce approximately 22,000 tonnes (18.3 million litres) of bio oil per year (50,137 litres/day) [43]. This implies 1 Ton/day of wood residue generates 501.4 litre/day of Bio-oil. Thus,

$$\text{Bio - oil Generated (litres / day)} = 501.4 \times \text{Wood Residue Used (Tons / day)} \quad \dots\dots\dots 4$$

The bio-oil cost was calculated to be \$1.21/gal (₦50/litre) for 100 tonne/day plant size [44]. [1 gallon = 3.785 litres, 1\$ = ₦155]. The total amount of bio-oil that can be realized from wood residue generated from the areas of study using pyrolysis is shown below in table 3.1.

**Table 3.1: Quantity and Amount of Bio-oil Liable to be realized from Wood Residue**

Cities	Wood Residue (Tons/day)	Bio-oil (Litres/day)	Bio-oil (₦/litre/day)
Lagos	807.7	404,980.8	20,249,040
Abeokuta	1,335.4	669,569.6	33,478,480
Ibadan	65.5	32,841.7	1,642,085
Ilorin	69.8	34,997.7	1,749,885
Ado-Ekiti	15.1	7,571.1	378,555
Akure	14.4	7,220.2	361,010
Ile-Ife	8.1	4,061.3	203,065
	<b>Total = 2,316</b>	<b>Total = 1,161,242.4</b>	<b>Total = ₦58,062,120/day</b>

## DISCUSSION

The problem of solid waste disposal has become an alarming environmental problem facing many cities in Nigeria with lack of effective waste management systems. However, sustainable energy can be generated from these wastes thereby putting an end to environmental pollution generated from them. In this study, the potential of bio-oil production from wood residue using pyrolysis had been examined in major cities of south-western Nigeria. Pyrolysis had been considered because of its superiority to other systems of waste-to-energy conversion as it operates at atmospheric pressure and modest temperatures with yields of bio-oil exceeding 70 wt % [28]. The major cities examined were Lagos, Abeokuta, Ibadan, Ilorin, Ado-Ekiti, Akure and Ile-Ife. The quantity of wood residue generation in different cities of consideration is shown in table 1. The high value of wood residue generation from Abeokuta is a result of its favourable environmental condition which allows afforestation and thus, encourages sawmilling industries while the contribution from Lagos results from her industrial and over-population influences. The population of Lagos has been reported be 10.3 million as at 1990 [45] while the population of Ibadan was reported to be approximately 1.4 million as at 2006 [46]. Less wood residue contribution from other cities (besides Ibadan and Ilorin) is due to their non-industrial nature and less dense population. The total quantity of wood residue generated was 2,316 Tons/day (845,340 Tons/year) with the potential of producing 1,161,242.4 litres/day ( $\approx$  424 million litres/year) of bio-oil using pyrolysis. The liable revenue to be generated from the sale of this bio-oil at \$1.21/gal (₦50/litre) is ₦58,062,120/day ( $\approx$  ₦21.2 billion/year). The price of this potential bio-oil at ₦50/litre is quite lower than the current price of diesel (₦180/litre) in which both are being used in many static applications such as boilers, furnaces, engines and turbines for electricity generation. Hence, adequate consideration should be given to this alternate means of energy generation thereby, reducing over-dependence on fossil fuels which are very expensive for industrial purposes.

## CONCLUSION

The potentials of waste-to-energy system in Nigeria has been examined by considering the potential of bio-oil production from wood residue generated in major cities of south-western Nigeria using pyrolysis. Our government should execute substantial capital project on this process as this serves as means of internal revenue generation which can equally be used in providing lacking infrastructural facilities in major cities of Nigeria. Also, this serves as effective way of reducing volume of wastes (detrimental to health) that are generated exponentially on daily basis. Nevertheless, overdependence of stakeholders on fossil fuels will be discouraged as bio-oil (lesser price) may be used as substitute for diesel in many static applications such as boilers, furnaces, engines and turbines for electricity generation in most industries. However, effective techno-economic analysis of the pyrolysis process is very important in order to know the capital and operating costs involved in the process which allows determining total profit that can be realized based on the available wood residue in our environment. Investigations into pyrolysis process optimization of wood residue should not be left out to have optimum bio-oil production. Nevertheless, the heating value of bio-oil produced from our wood residue by pyrolysis should be checked with the corresponding fossil fuel (diesel) to know if the latter can fully displace the former.

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