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Research Article

A MULTICRITERIA DECISION BASED ASSESSMENT OF AGRICULTURAL SOLID WASTES AS POTENTIAL FEEDSTOCK FOR ELECTRICITY GENERATION IN NIGERIA

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ABSTRACT

An effective method of managing solid wastes from agricultural processing is through thermochemical conversion to energy-dense and carbon-neutral energy products; which relieves the issue of depleting global resources, solves the problem of over-reliance on fossil fuel, reduces the impact on the environment, and brings economic benefits. In this study, the suitability of agricultural solid wastes as potential feedstock for electricity generation in Nigeria via a combined pyrolysis–steam power plant technology was assessed. Technique for order of preference by similarity to ideal solution was used to identify the most appropriate raw material for electricity generation among the considered alternatives – rice husk, corncob, and palm kernel shell. These wastes showed high electricity generation potential (232 – 2077 GWh per annum), high profitability index, and high carbon reduction benefit (about 1428 kg CO_2 eq. / m^3 of bio-oil).

Keywords: Waste-to-energy; Agricultural solid waste; Multi-criteria decision analysis; Environmental impact assessment; Cost-benefit assessment; Pyrolysis.

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1. INTRODUCTION

Agricultural wastes are unwanted non-product outputs produced as a result of various agricultural activities [1]; usually from the cultivation and processing of agricultural produce, as well as effluent from animal husbandry. Agricultural wastes could be solid, liquid or slurry, depending on the type of activities and system employed on the farm. The quantity of these wastes has been on an increase globally, majorly due to an upward trend in agricultural production; with organic waste constituting about 80% of the total generated waste [2]. Global estimates of agricultural wastes are quite rare to find in waste collection surveys, although it has been found that they contribute significantly to the total waste streams of nations [2]. The quantity of agricultural wastes is calculated indirectly in relation to expected yields and harvesting levels, therefore there is usually a wide range of annual estimates. However, it has been indicated that approximately 998 million tonnes of agricultural waste are produced annually around the globe [3]. In Malaysia, about 1.2 million tonnes of agricultural waste is disposed into landfills annually. Similarly, Asian countries such as Malaysia, Philippines, Singapore, Thailand, China, Korea, and Japan have been reported to generate 0.122, 0.078, 0.165, 0.096, 0.12, 0.15, and 0.17 kg/capacity/day of agricultural waste [4].

In developing regions of the world, the bulk of agricultural solid wastes (ASWs) are dumped in landfills or burned uncontrollably onsite. ASWs may however be used as compost, converted into animal feed or fertilizer, or used as adsorbents in the elimination of heavy metals; they can also undergo anaerobic digestion, pyrolysis, or direct combustion [3]. ASWs such as palm oil fuel ash, palm kernel shell ash, and rice husk ash have been confirmed as effective modifiers of subgrade soil [5]. Furthermore, ASWs have been utilized as substrates for producing industrial products such as enzymes, aroma, and flavor compounds [6]. In Malaysia and Brazil, banana peel and sugarcane fibers are used for papermaking pulp; husk, straw, and cow dung are used to produce biogas, ethanol from sugarcane has been used to produce green polythene while rice husk is notable for electricity production [7]. Effective utilization of ASWs entails using these residues almost quickly or storing them under a suitable condition which reduces spoilage and enhances the suitability of the residues for the desired use [2].

An effective method of managing ASWs is by conversion to energy; which could involve the thermochemical, biochemical or physical conversion of these wastes into clean energy [8]. The conversion of ASWs to energy-dense and carbon-neutral energy products relieves the issue of depleting global resource, solves the problem of over-reliance on fossil fuel, reduces the impact on the environment, and brings economic benefits; it also promotes rural development and enhances the provision of fuels that are needed to power the energy and transportation sectors [9,10]. Over the past decades, progress has been achieved on the techniques for the use of ASWs for energy production; notable among these are liquefaction, hydrolysis, enzymolysis, and solidification technologies (i.e. briquetting), direct combustion (i.e. incineration), bio-gasification, pyrolysis, gasification as well as recovery of landfill gas. In addition, major energy products derivable from the management of ASWs – such as corncob (CC), rice husk (RH), and palm kernel shell (PKS) – include bio-diesel, bio-kerosene, bio-gasoline, fuel ethanol, biogas, pyrolysis gas, and electricity [11,12].

CC is the residue obtained after corn grains are shelled from the cob. In most developing countries, CC is usually disposed of and burnt on the farm in preparation for the next farming season, despite having great potential as an energy resource. It is dense and has low sulfur and nitrogen contents which makes it emit fewer sulfur oxides when combusted as compared with fossil fuels [13]. CC is a potential thermochemical feedstock with an approximate heating value of 19.14 MJ/kg, which makes it a suitable substitute for coal; also, electricity has been generated from CC's char through several waste-to-energy technologies [13,14]. On the other hand, RH (or hull) is the hard protective covering of rice grains which is discarded as a by-product during the process of rice milling. It is highly porous and lightweight; and it contains about 75-90% organic constituents namely: cellulose, hemicellulose, and lignin. Its other constituents are mineral components which include alkalis, trace elements, and silica [15]. RH is about 20% of the weight of rice and has a calorific value of approximately 15MJ/kg [16]. In a study carried out in Pakistan, it was estimated that approximately 1328 GWh of electricity can be generated annually from the use of RH residues [16]. In another study, 4947MWh of electricity per annum was produced from 6432 tons of hulls using fluidized bed combustion technology [17]. Ame-Oko et al. [18] observed that a gasifier-gas turbine plant is the most efficient means of utilizing RHs for combined heat and power generation. Also, PKS, which is obtained during the extraction of palm oil from the palm nut, is a good quality biomass suitable for energy production due to its uniform size distribution, low moisture content, and a calorific value that is moderately higher than other lignocellulosic biomass [19]. The utilization of oil palm biomass waste as a renewable energy feedstock for electrical power generation was evaluated by Obuka et al. [20] and it was established that 897kg of empty fruit bunches generated about 1.7MW of power. Similarly, Kareem et al. [21] reported findings on the generation of electricity produced from PKS using a small-scale steam power plant.

Worldwide, the main energy-generating systems rely majorly on the utilization of fossil fuels for electricity generation, and developing nations are not left out. Currently, there is an increasing global pressure on power generating systems, especially in developing countries, to adopt clean energy sources [13]. Presently, in Nigeria, the major national energy supplies are from fossil fuels and firewood which are depleting at an alarming rate [22]. As of 2015, Nigeria was generating about 3080MW of electricity, mostly from the combustion of fossil fuels – about 99%, to meet an estimated demand of 10,000MW [23,24]. Research has shown that the production of energy from the combustion of fossil fuels is detrimental to the environment, as it contributes largely to the emission of greenhouse gases and the release of toxic air pollutants [9,25]. In the nation's power sector, the generation of electricity is faced with a lot of setbacks; as about 50% of the nation's installed capacity is mostly unavailable due to inefficient utilization of the available energy resources and poor infrastructures [26]. As a result of the increasing energy demands, there is thus a need for diversification in the generation of electricity in Nigeria; and so far the country has failed to take full advantage of the emerging global waste-to-energy technological innovations to meet its present energy need [26].

Nigeria is one of the developing countries that is still lagging in harnessing the beneficial utilization of ASWs [27]. The country is naturally endowed with abundant renewable energy resources but it is not sufficiently exploring alternative means of generating electricity, hence the reason for this research. This work aims at assessing the suitability of ASWs as suitable feedstock for the generation of electricity in Nigeria via a combined pyrolysis – steam power plant technology, by focusing on the techno-economic and environmental benefits. In this research, ASWs to be considered are RH, CC, and PKS, as they are abundant and cheap in

Nigeria. Furthermore, through the adoption of empirical analysis of key performance indices, the best material that can be utilized for electricity generation through combined pyrolysis – steam power plant technology will be established using multicriteria decision-based analysis.

1.1. Biomass-to-energy via pyrolysis

The discourse on renewable energy has attained a level of growing importance, mainly due to the continuous use of fossil fuels for energy generation; which has greatly contributed to the issues of global climate change, degradation of the environment, and the gradual decline of the available fossil energy resources [9,28]. To therefore promote clean energy utilization, biomass has been considered as one with huge potential to supplement the declining fossil fuel resources [28]. Biomass is widely available in various forms such as dedicated energy crops, municipal solid waste as well as agriculture and wood residues. Among these various alternatives, ASW represents the feedstock with the greatest potential to develop the growing bio-energy industry: it has minimal or low-cost value and it is readily available in huge quantities for the production of bio-products [29]. The conversion of ASWs to energy may be physical, biological, chemical, or thermal [30]. Pyrolysis, a typical thermochemical conversion process, is a desirable route for the use of ASWs and has been extensively adopted for the conversion of biomass into solid, liquid, and gaseous products [31].

Pyrolysis, also referred to as incomplete gasification, is the thermal degradation or decomposition of fuel in the absence of an oxidizing agent, generally in an oxygen-free environment [32]. Generally, pyrolysis can either be a slow or fast process: slow or conventional pyrolysis has been widely adopted for charcoal production at the suitable conditions of low heating rate, high temperature, and long gas residence time (usually from 5 to 30 minutes) while fast pyrolysis process is characterized with high-temperature and rapid heating of biomass in an oxygen-free environment [31]. The rapid heating of biomass in such an oxygen-free environment results in the generation of organic vapor; which is mainly a mixture of fragments of biomass constituents', namely: lignin polymers, hemicellulose, and cellulose. The condensation of these vapors leads to the production of bio-oil – a freely flowing organic liquid. The non-condensable gases are collected and mostly used to generate energy for the pyrolysis process. The remaining solid byproduct is known as Bio-char, which is characterized by high carbon content [33].

Industrial application of pyrolysis is mostly used to maximize bio-oil yield through fast pyrolysis [32] and such fuel has been extensively utilized in static applications as an alternative to fossil fuels, such as in diesel engines for power generation as well as in industrial kilns and furnace [34]. Unlike the aforementioned energy conversion systems, the boiler component of the steam power plant is reputable as a viable alternative technology for the direct combustion of low calorific fuels, with a high level of moisture content, like bio-oil [35]. The successful utilization of bio-oil and its blends with ethanol in various power plant combustors has been reported, such as circular jet spray combustor [36], atmospheric pressure spray burner [37], industrial dual-fuel boiler [38] and oil-fired commercial boiler [35].

1.2. Application of multi-criteria analysis (TOPSIS) in Waste-to-energy studies

In recent times, the use of quantitative multicriteria techniques for the determination of the best option among applicable alternatives has been extensively proposed and utilized for various technological and socio-economical evaluations [39]. Multicriteria decision analysis (MCDA) is a decision aiding tool that has found widespread applications in addressing complex problems having conflicting points of view, high uncertainty, diverse types of information and data, multi perspectives and interests, conflicting objectives, as well as in the assessment of evolving and complex socio-economic and biophysical systems [40,41]. Commonly used and widely accepted MCDA technique has been itemized by Achillas et al. [42] as: “multi-attribute utility theory (MAUT), preference ranking organization method for enrichment evaluations (PROMETHEE), analytic hierarchy process (AHP), analytic network process (ANP), ELimination Et Choix Traduisant la REalitè (ELECTRE), measuring attractiveness by a categorical based evaluation (MACBETH), techniques for order of preference by similarity to ideal solution (TOPSIS)”.

Prominent among these MCDA techniques is TOPSIS, which stands out due to its simplicity, ease of use, and greater capability for computational efficiency; it is a viable approach that allows the ranking of alternative solutions in a multicriteria decision analysis of a complex problem and it relies on the Euclidean distance principle to determine the best alternative, which is assumed to have the shortest and longest distance from the positive ideal solution and the negative ideal solution respectively [43]. Several research outputs on the use of MCDA techniques for the assessment of waste-to-energy technology have been widely reported in the literature. In Australia, Begum et al. [44] assessed various alternative waste technologies - that help redirect waste away from landfills, recover energy and reduce impacts on the environment - based on criteria such as capital cost, complexity, public acceptability, landfill diversion, and energy recovery index. Similarly, Siregar et al. [45] evaluated alternative technology for waste management in Indonesia and concluded that anaerobic digestion gave satisfactory results.

Yap and Nixon [46] assessed the application of MCDA for waste management and energy planning in both India and the UK, by focussing on a range of financial, technological, economic, and environmental factors. Due to differences between these countries in terms of technical and socio-economic challenges; the author established that the preferred technology is anaerobic digestion and gasification for India and UK respectively. A combined fuzzy analytic network process and TOPSIS approach were adopted by Wang et al. [47] for the siting of waste-to-energy plants in Vietnam, to achieve improved economic and environmental benefits. Michailos and Webb [39] carried out a comprehensive TOPSIS based assessment of the sustainable pathway for the conversion of bagasse to ethanol, focusing on criteria such as energy efficiency, production cost, mass efficiency, and fossil energy input; the result revealed the biochemical route as the most sustainable pathway. Nonetheless, the hybrid route that combined the features of both biochemical and thermochemical routes was indicated to be promising.

In Nigeria, the use of TOPSIS assessment in site selection for waste-to-energy technology has also been investigated [48]. TOPSIS combined with an entropy-weighted technique was applied by Alao et al. [43] for the selection of appropriate waste-to-energy technology using the Lagos state’s waste stream for electricity generation; It was established that anaerobic digestion and pyrolysis were the topmost technologies for the efficient conversion of waste to electricity. Equally, it was indicated that high environmental gains and electricity generation potential can be achieved by adopting the combination of anaerobic digestion, landfill gas recovery, and pyrolysis technologies for the simultaneous treatment of the various components of the waste stream. Despite the countless pieces of literature on the application of TOPSIS for waste-to-energy technology assessment, there seems to be a dearth of information on its use for the assessment of ASWs as suitable feedstocks for electricity generation in Nigeria. The aim of this study is therefore to also adopt the entropy-weighted TOPSIS technique for the selection of appropriate ASW that will be suitable for the generation of electricity via combined pyrolysis – steam power plant technology in Nigeria.

2. EXPERIMENTAL

2.1. Quantification and characterization of selected ASWs

In this study, secondary data, obtained from existing literature, served as the basis for the characterization and quantification of the selected ASWs. Data on elemental composition (ultimate analysis) and proximate analysis of the selected ASWs were obtained and averaged (including standard deviation) [30-31; 33-34; 49-50]. For ease of comparison, ultimate and proximate analyses data, which were reported on dry-ash and as-received bases, were converted to a dry-mass basis by adopting the methodology outlined in the European standard EN 15296:2011 [51]. As proposed by Friedl et al. [52], the energy content (High heating value) for each of the selected ASWs was estimated using Eq. 1.

$$HHV_i = 3.55C^2 - 232C - 2230H + 51.2C \times H + 131N + 20600 \qquad 1$$

Where HHV is the high heating value (in MJ/kg); C, H, and N represent the percentage mass fraction of carbon, hydrogen, and nitrogen content of each ASW.

The estimation of the amount of solid waste generated per annum ($P_{i.n}$) from the respective biomass, in kg-biomass waste/year, can be determined using Eq. 2; which was adapted from the research output of Ogunjuyigbe et al. [53]:

$$P_{i.n} = C_r \times Q_{0.i}\,(1 + r)^n \times M \qquad 2$$

Where, C_r is the waste collection rate taken as 0.74, $Q_{0.i}$ is the base year biomass production rate in kg-biomass/year (2020 was chosen as the base year), *i* represent the considered biomass and *n* is the extrapolation time (2020 to 2040), *r* represent the biomass average compound growth rates for the projection of its annual production rate, M is the mean waste generated (in kg-waste per kg-biomass – it is assumed to be constant for the years of projection). Tables 1 and 2 present the biomass production rate, the average compound growth rate for individual biomass, and the average waste generation rate.

Table 1: Production and growth rates of Biomass

Biomass	Production Rate		Average growth rate	Reference
	Annual Production (10^6 kg)	Base year		
Rice	3780	2018	4.96	[54,55]
Corn	8180	2015	5.52	[27,56]
Oil Palm	2530	2013	4.7	[57,58]

Table 2: Average waste generation rate

ASWs	Waste generation rate (kg-waste per kg-biomass)		
	Mean Value (M)	Standard deviation	References
RH	22	2	[59]
CC	19	1	[60]
PKS	6	1	[61]

2.2. Evaluation of electricity generation potential

To ascertain the electricity generation potential of the selected ASWs as suitable feedstock for a thermochemical conversion pathway, via pyrolysis technology, a combined pyrolysis-steam power plants model was adopted. Combustion of pyrolysis product (bio-oil) for electricity generation offers several advantages such as reasonable economic cost and negligible pollutant emission in comparison to other thermochemical conversion processes, usually due to its reduced operating temperature and inert working environment [32]. In this study, as depicted in Fig. 1, bio-oil, as received from pyrolysis plant, is directly fed into a steam-powered plant – which comprises a boiler, steam turbine, and a generating set. Depending on the adopted technology, the raw material can undergo several pretreatment operations before being fed into the boiler. The boiler raises the temperature of the process water turning it into steam, which in turn drives the turbine leading to the generation of mechanical energy. The interaction between the turbine and the generating set leads to the conversion of the produced mechanical energy into the required electrical energy.

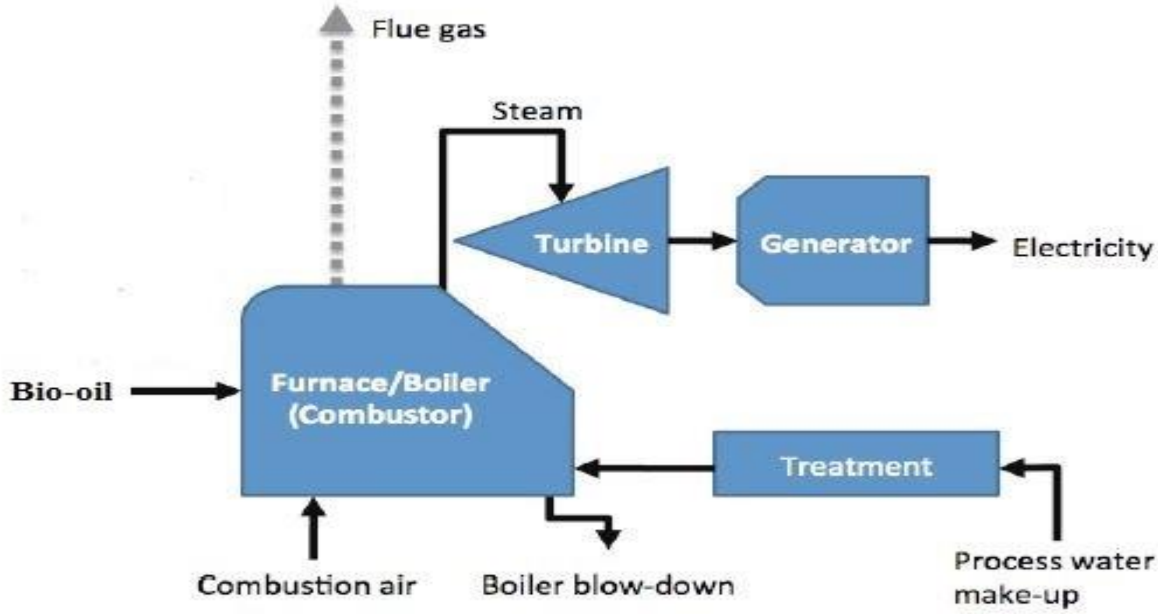


Fig.1. Bio-oil process flow diagram (Source: Adapted from Jorgenson et al. [62])

Table 3 presents the yield and the physicochemical characteristics of bio-oil from the selected ASWs; which were sourced from existing literature [29–31,33,34,63]. The average yield of bio-oil was utilized for this study and the inherent uncertainty in these data was computed using standard deviation methodology with the aid of an Excel spreadsheet software.

Table 3: Yield and physicochemical characteristics of the selected ASWs' bio-oils.

Parameters	RH	CC	PKS
% Yield	39.15±0.80	45.18±1.86	47.47±1.16
HHV (MJ/kg)	17.71	15.80	17.90
Density (kg/m^3)	1058	1220	1051
Elemental compositions (%)			
C	31.95	38.10	47.60
H	10.16	8.00	8.10
O	57.42	53.18	43.66
N	0.38	0.70	0.60
S	0.09	0.02	0.04

According to Alao et al. [43], Eqs. 3 and 4 can be used to calculate the annual and average electrical energy (in GWh/annum) that are obtainable from the use of the respective ASW.

$$E_{i.n} = \frac{P_{i.n} \times Y_{b.i} \times HHV_{b.i} \times \eta_s}{C_f \times 1000} \tag{3}$$

$$E_{i.avg} = \frac{1}{n}\sum_{j=1}^{n} E_{i.n} \tag{4}$$

Where the values: $E_{i.n}$ is the amount of electricity generated per annum, $E_{i.avg}$ is the average amount of electricity generated per annum (the electricity generation potential), 1000 represent the conversion index from MWh to GWh respectively, $P_{i.n}$ is the amount of ASW generated per annum, $Y_{b.i}$ is the mean bio-oil yield (in % or kg-bio-oil / kg-biomass waste) while $HHV_{b.i}$ represents the high heating value of the bio-oil obtainable from the respective ASWs (in MJ / kg-bio-oil) (table 3). C_f is the conversion factor from MJ to MWh; according to Hofstrand [64], 3.6 MJ equals 1 KWh (or 3600 MJ equals 1 MWh).

Similarly, η_s is the overall efficiency of the steam-powered plant and it is a function of several other efficiencies; it can be obtained as:

$$\eta_s = \eta_{pt} \times \eta_e \tag{5}$$

$$\eta_{pt} = \eta_c \times \eta_{th} \times \eta_t \tag{6}$$

Where, η_{pt} is the plant's thermal efficiency, η_c is the boiler combustion efficiency taken as 0.99 for bio-oil combustion, η_{th} is the boiler's thermal efficiency taken as 0.80, η_t is the turbine efficiency with a value of 0.65 while η_e is the effective electrical efficiency taken as 0.75 [62; 65-67].

The nominal size of the power generating infrastructure can be determined using Eq. 7 as proposed by Ogunjuyigbe et al. [53]:

$$P_{s.i} = \frac{E_{i.avg} \times 1000}{8760 \times 0.85} \tag{7}$$

Where $P_{s,i}$ is the plant size (in MW), 1000 is used to convert $E_{i,avg}$ from GWh to MWh, 8760 denotes the amount of time available in a year while 0.85 is the capacity factor (CF).

2.3. Environmental impacts assessment

The environmental burdens as a result of the use of pyrolysis products for electricity generation were evaluated using the Eco – indicator impact assessment methodology. This is an easy-to-use approach that allows different environmental effects to be weighed and summed to achieve a single score for environmental impacts evaluation, it is measured and expressed as Eco–point (Pt); the evaluation comprises various components, namely: characterization, normalization, and weighted evaluation as well as life cycle inventory (LCI) [68-69]. As depicted in Fig. 2, the system boundary focuses on the conversion of the constituent bio-oil into electrical energy; however, the environmental burdens associated with bio-oil production, from gate-to-gate, before energy generation, was equally taken into consideration. It was assumed that the energy requirement for bio-oil production was met through the combustion of the pyrolysis byproducts – biochar and syngas, hence the biogenic CO_2 emission produced during the process was not taken into consideration [38]. Technically, the degradation of biomass is regarded as carbon neutral because CO_2 evolved during combustion is equal to the CO_2 utilized by biomass for photosynthesis during its growing stage [70].

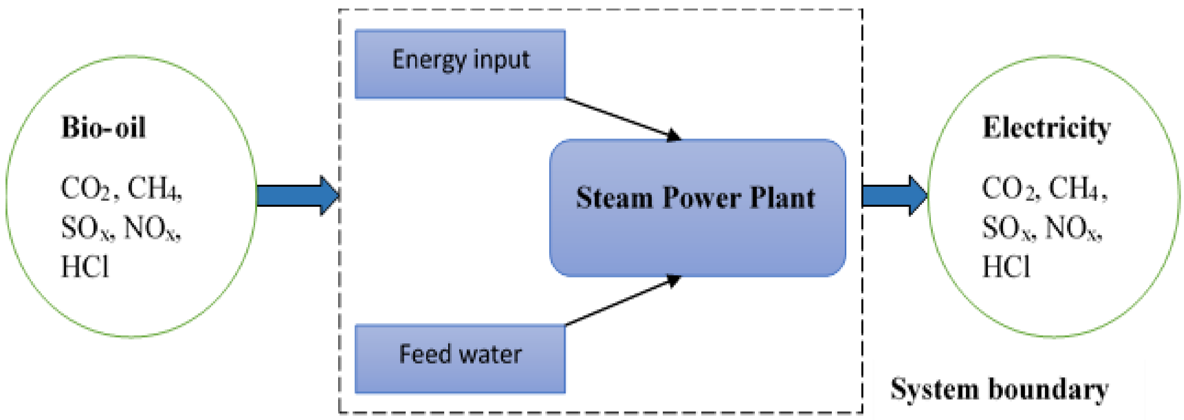


Fig.2. Systems description for electricity generation using bio-oil

1 m^3 of bio-oil, consumed for electricity generation, was adopted as the functional unit. The

inventory of relevant emissions (LCI), classification, and subsequent assignment of the inputs and outputs of LCI to the considered impact types (characterization) were done by adopting the ISO-compliant life cycle assessment technique – a midpoint approach; which is a method that was defined and standardized according to the procedural framework of ISO 14040 – 14043, by the international standards organization [71]. In this study, the considered categories of impact are global warming (GWP) and acidification potentials (AP). Eqs. 8 to 12 were used to ascertain the extent of damage to the ecosystem according to the procedure specified by Salami et al. [25] and Ayodele et al. [72].

$$E_{p.e} = E_{f.e} \times E_q \tag{8}$$

Where $E_{p.e}$ is the emission of constituent gases for each impact category (kg-pollutant per annum). E_q is the energy equivalent index. It represents the average energy content of the total amount of bio-oil consumed for electricity generation (GJ/annum). $E_{f.e}$ is the emission factor (kg/GJ). E_q can be obtained using Eq. 9:

$$E_q = \frac{P_{i.n} \times Y_{b.i} \times HHV_{b.i}}{1000 \times n} \tag{9}$$

All terms in Eq. 9 have been previously defined: $P_{i.n}$ (kg-biomass waste/year), $Y_{b.i}$ (in % or kg-bio-oil / kg-biomass waste), $HHV_{b.i}$ (MJ / kg-bio-oil), 1000 is used to convert from MJ to GJ.

Furthermore, Eqs. 10 to 12 were used to obtain the equivalent contribution of a product life cycle to an effect p (impact category), both in kg-pollutant equivalent per annum (E_p) and kg-pollutant equivalent per m^3 of annual average bio-oil consumption (H_p):

$$E_p = \sum E_{p.e} \times Ch_{f.e} \tag{10}$$

$$H_p = \frac{E_p}{V_{i.bio-oil}} \tag{11}$$

$Ch_{f.e}$ is the characterization factor, $V_{i.bio-oil}$ is the average volume of bio-oil consumption per year (m^3/annum). Table 4 shows the required data for LCI, characterization, and impact assessment.

$V_{i.bio-oil}$ is obtained by dividing the average mass of bio-oil consumed per annum for electricity generation by the density ($\rho_{b.i}$) of the respective bio-oil (Table 3), i.e.:

$$V_{i.bio-oil} = \frac{P_{i.n} \times Y_{b.i}}{\rho_{b.i} \times n} \qquad 12$$

Table 4: Input factors for life cycle impact assessment

Impact category	Emission	Biomass emission factor (kg/GJ)	Characterization factor
GWP	CO_2	2.69	1
	CH_4	9.09×10^{-3}	23
AP	SO_x	2.33×10^{-1}	1
	NO_x	4.67×10^{-1}	0.7
	HCl	3.79×10^{-3}	0.88
Reference		Steele et al. [38]	Salami [71]

Similarly, according to Goedkoop [73], the weighted environmental burden on the ecosystem can be ascertained using Eq. 13.

$$I = \frac{W_p \times H_p \times F_p}{N_p} \qquad 13$$

I represents the indicator value, F_p is the reduction factor, N_p is the normalization value while W_p is the damage weighting factor (which is taken as one). Table 5 presents the required data for the quantification of the environmental burdens associated with the use of bio-oil for electricity generation.

Table 5: Factors for determining the extent of ecosystem impairment

Impact category	Normalization value	Reduction factor	References
Global warming potential	1.31×10^4	2.5	Goedkoop [73]
Acidification potential	1.13×10^2	10	Goedkoop [73]

In addition, the net CO_2 reduction benefit, due to the utilization of bio-oils for the generation of electricity, was also considered and quantified using Eqs. 14; taking the net CO_2 emission of fuel oil as the reference – which has a value of 1483 kg CO_2 eq. per m^3 of consumed bio-oil [68].

$$CO_2 \ reduction \ benefit = H_p.CO_{2.ref} - H_p.CO_{2.bi} \quad (14)$$

Where $H_p.CO_{2.bi}$ is the net CO_2 emission for the respective bio-oil and $H_p.CO_{2.ref}$ is the equivalent CO_2 emission of the reference fuel (both in kg CO_2 eq. per m^3 of fuel).

2.4. Cost-benefit evaluation

NPV, profit/loss, and production cost were taken into consideration as suitable indices for assessing the economic viability of the respective ASWs utilization for electricity generation via combined pyrolysis – steam power plant technology. The NPV of a project is a relatively simple method that sums the discounted annual cash flows from the inception of the project to its final disposal and it is widely accepted for the economic appraisal of energy-related projects [74]. Similarly, the production cost is a significant index for financial feasibility studies as it takes into consideration the capital investment and operational costs [39]. Capital investment cost mainly comprises the equipment supply and installation costs, while the operation and maintenance cost is the cost required for the day-to-day running of an equipped facility and comprises fixed and variable costs [75].

The profit/loss was ascertained by determining the difference between the average annual revenue and production cost. The assumptions made for the assessment of the economic benefits are presented in Table 6.

2.4.1. Determination of NPV

According to Ogunjuyigbe et al. [53], NPV can be calculated using Eq. 15:

$$NPV = \sum_{n=0}^{N} \frac{F_n}{(1+d_r)^n} = F_0 + \frac{F_1}{(1+d_r)^1} + \frac{F_2}{(1+d_r)^2} + \ldots\ldots + \frac{F_N}{(1+d_r)^N} \quad 15$$

Where, d_r is the annual real discount rate, F_n is the net cash flow rate and N is the total number of projected years. Both F_n and d_r can be quantified using Eqs. 16 and 17 respectively.

$$F_n = R_{ev.i} - C_{inv.i} - C_{O\&M.i} - C_{tax} \quad 16$$

$$d_r = \left(\frac{1+d_n}{1+e}\right) - 1 \quad 17$$

$R_{ev.i}$ represents the total revenue, $C_{inv.i}$ is the total capital investment cost, $C_{O\&M.i}$ is the operation and maintenance cost, C_{tax} is tax cost, d_n is the nominal discount rate, e is the inflation rate while *i* represents the various feedstock.

2.4.1.1 Estimation of Capital investment and operational costs

$C_{inv.i}$ And $C_{O\&M.i.}$ for the respective feedstock can be determined using the following equations:

$$C_{inv.i} = C_p \times P_{s.i} \times 1000 \quad 18$$

Where, C_p is the plant unit cost and $P_{s.i}$ is the installed plant capacity (Eq. 7).

Similarly, the operating cost can be quantified using Eqs. 19 and 20:

$$C_{O\&M.i} = FC + VC_{f.i} + C_{f.i} \quad 19$$

$$C_{O\&M.i} = (FC_f \times P_c \times 1000) + (VC_f \times E_{i.n} \times 1000) + (Y\% \times P_{i.n} \times C_{oil}) \quad 20$$

Where FC is the fixed cost, $VC_{f.i}$ is variable cost (excluding fuel cost), $C_{f.i}$ is the fuel cost, FC_f is the fixed cost index, VC_f is the variable cost index and C_{oil} is the mean cost of bio-oil. C_{oil} .was assumed to be \$0.18/kg for RH, \$18/GJ (\$0.28/kg) for CC and \$0.27/kg for PKS [76–78]. FC was assumed to be constant through the life cycle of the project.

2.4.1.2. Estimation of total revenue cost and tax

R_{ev} and C_{tax}can be determined using the equations specified by Michaelides [74]:

$$R_{ev.i} = \text{revenue from electricity} + \text{bond revenue} + \text{salvage value} \tag{21}$$

$$\text{Revenue from electricity} = E_{i.n} \times C_e \times 1000000 \tag{22}$$

Where, C_e is the cost of electricity; which is the projected average cost for the year 2020 to 2024 (valued at 310 Naira per $ but was corrected for the present $ rate of 360 Naira) [79].

$$C_{tax.i} = (\text{taxable income}) \times (\text{tax rate}) - (\text{tax credit}) \tag{23}$$

$$\text{Taxable income} = (\text{pretax income}) - (\text{depreciation}) \tag{24}$$

$$Pretax\ income = R_b - C_c - C_{O\&M.} - I_b \tag{25}$$

Where: R_b is the total revenue excluding bond revenue, C_c is the closing cost, while I_b is the bond interest; depreciation was obtained using the straight-line method.

2.4.2. Determination of annual production cost

The production cost can be determined using the following equations [39]:

$$\text{-}Production\ cost_i = \frac{Total\ annual\ cost(TAC_i)}{Production\ rate_i} \tag{26}$$

$$TAC_i = ACC_i + C_{O\&M.i} \tag{27}$$

Where ACC is the annualized capital cost and it can be determined using:

$$ACC = C_{inv.i} \times \frac{i_c \times (1 + i_c)^N}{-1 + (1 + i_c)^N} \tag{28}$$

Where i_c is the cost of capital and it is equivalent to the nominal discount rate.

Table 6: Factors used for economic benefit analysis

Factor	Value	Unit	Reference
Electricity cost	0.2712	$/KWh	NERC [79]
Inflation rate	9.4	%	Ogunjuyigbe et al. [53]
Nominal discount rate	10	%	Ogunjuyigbe et al. [53]
Marginal tax rate	30	%	Ogunjuyigbe et al. [53]
Project lifetime	20	Years	Alao et al. [43]
Interest rate	10	%	Alao et al. [43]
Cost of capital	10	%	Michailos and Webb [39]
Capacity Factor	0.85	-	Ogunjuyigbe et al. [53]
Fixed cost index	10.53	$/KW	Tidball et al. [80]
Variable cost index	3.17	$/MWh	Tidball et al. [80]
Plant unit cost	652	$/KW	Tidball et al. [80]

2.5. Optimization model for decision making

The entropy-weighted TOPSIS technique was adopted for the determination of the best alternative among the selected ASWs for electricity generation. TOPSIS technique is a prominent methodology that simultaneously considers the relative closeness of various alternatives to the positive and negative ideal solutions; the best alternative is taken as the one that is closest to the positive ideal solution and farthest from the negative ideal solution [39]. To select the best alternative, the decision criteria considered are electricity generation potential, NPV, carbon reduction benefit, annual production cost, and ecosystem impairment. According to Alao et al. [43] and Pavić and Novoselac [81], the TOPSIS stepwise procedure for the selection of the best alternative ASW for the optimum generation of electricity via pyrolysis technology with maximum economic benefit and minimal environmental degradation is summarized as follows:

Step 1: Prepare the initial table and decision performance matrix as depicted in Table 7 and Eq. 29 respectively, where A_1 to A_m represent the alternatives and x_{ij} represent the positive rating of alternative *i* to criterion j. Criteria x_1 to x_k are benefit (monotonically increasing preference) while criteria x_{k+1} to x_n are non-benefit (monotonically decreasing preference).

Table 7: Initial table for TOPSIS method (m alternatives by n criteria)

Criteria	Cr.1	Cr.2	....	Cr.n
	x_1	x_2	....	x_n
Weights	w_1	w_2	....	w_n
A_1	x_{11}	x_{12}	....	x_{1n}
A_2	x_{21}	x_{22}	....	x_{2n}
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
A_m	x_{m1}	x_{m2}	....	x_{mn}

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{29}$$

Step 2: Since x_{ij} presents values of different criteria with a different unit, hence x_{ij} is thus replaced by weighted normalized values a_{ij} that can be determined using Eq. 30:

$$a_{ij} = w_j \times r_{ij} \tag{30}$$

Where r_{ij} and w_j are the normalized values and weight of each criterion respectively, both can be calculated using Eqs. 31 and 32:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{31}$$

$$w_j = \frac{1 - E_j}{\sum_j^n (1 - E_j)} \tag{32}$$

E_j can be determined using

$$E_j = -\frac{\sum_i^m P_{ij} \ln P_{ij}}{\ln m} \tag{33}$$

Similarly, P_{ij} can be calculated by adopting Eq. 34:

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{34}$$

E_j is the entropy of criterion j and P_{ij} is the criteria value of alternative (i) under criterion (j).

Step 3: Determination of the positive ideal ($A^+ = a_1^+, a_2^+, \dots a_n^+$) and negative ideal ($A^- = a_1^-, a_2^-, \dots a_n^-$) solutions using Eqs. 35 and 36 respectively:

$$a_j^* = \begin{cases} \max a_{ij}, & for\ j = 1, \dots . k \\ \min a_{ij}, & for\ j = k+1, \dots . n \end{cases} \tag{35}$$

$$a_j^- = \begin{cases} \min a_{ij}, & for\ j = 1, \dots . k \\ \max a_{ij}, & for\ j = k+1, \dots . n \end{cases} \tag{36}$$

Step 4: Determination of the distance between the alternatives and the positive ($d^+ = d_1^+, d_2^+, \dots d_m^+$) and negative ideal ($d^- = d_1^-, d_2^-, \dots d_m^-$) solutions are obtainable using Eqs. 37 and 38 respectively:

$$d_i^+ = \sqrt{\sum_{j}^{n} (a_{ij} - a_j^+)^2} \tag{37}$$

$$d_i^- = \sqrt{\sum_{j}^{n} (a_{ij} - a_j^-)^2} \tag{38}$$

Step 5: The relative closeness to the ideal solution can be determined using:

$$D_i^* = \frac{d_i^-}{d_i^+ + d_i^-} \tag{39}$$

Step 6: Ranking of D_i^* in descending order according to the preference, maximum D_i^* is accepted as the best alternative.

3. RESULTS AND DISCUSSION

3.1. Results of assessment indicators

This section presents and discusses the indices for establishing the suitability of the various ASWs as a potential feedstock for the generation of electricity via a combined pyrolysis-steam power plant technology.

3.1.1. Quantity and physicochemical characteristics of the selected ASWs

Fig. 3 captures the huge amount of biomass waste that can be collected and processed for electricity generation in Nigeria; as depicted in the figure, the analysis of the obtained secondary data indicated that CC has the highest annual waste generation potential with the capacity to generate waste in the range of approximately $1500 \times 10^6\ kg$ in the year 2020 to about $4400 \times 10^6\ kg$ in the year 2040. In addition, RH ranked second with an average annual waste generation potential of about $1150 \times 10^6\ kg$ while PKS has the least annual waste generation potential that ranged from $150 \times 10^6\ kg$ to $400 \times 10^6\ kg$ between the years 2020–2040. Concerning energy content, as depicted in Table 8, the average HHVs of the biomass wastes ranged from 15.32 MJ/kg to 17.48 MJ/kg. Interestingly, PKS has the highest average HHV and as such has the greatest embedded energy available for bio-oil production and subsequent electricity generation. This is most likely to be as a result of its high volatile carbon content; feedstock with high volatile matter favors high conversion of biomass to bio-oil [33]. CC, which equally has high elemental and volatile carbon contents, has an HHV that is very close to that of PKS. However, aside CC that has HHV within less than 2 % standard deviation, the HHVs of the other two biomass wastes have a standard deviation within the range of 6 -7 %. This can be traced to the high variability of the input data to Eq. 1. Nonetheless, these biomass wastes, with HHV well above 8 MJ/kg and moisture content well below 20 %, are viable feedstock for bio-oil production [82]. Furthermore, all the waste materials have similar hydrogen content with sulfur and nitrogen contents that were all less than 1%; hence, the concerns about the emission of toxic pollutants are most likely to be minimal [49].

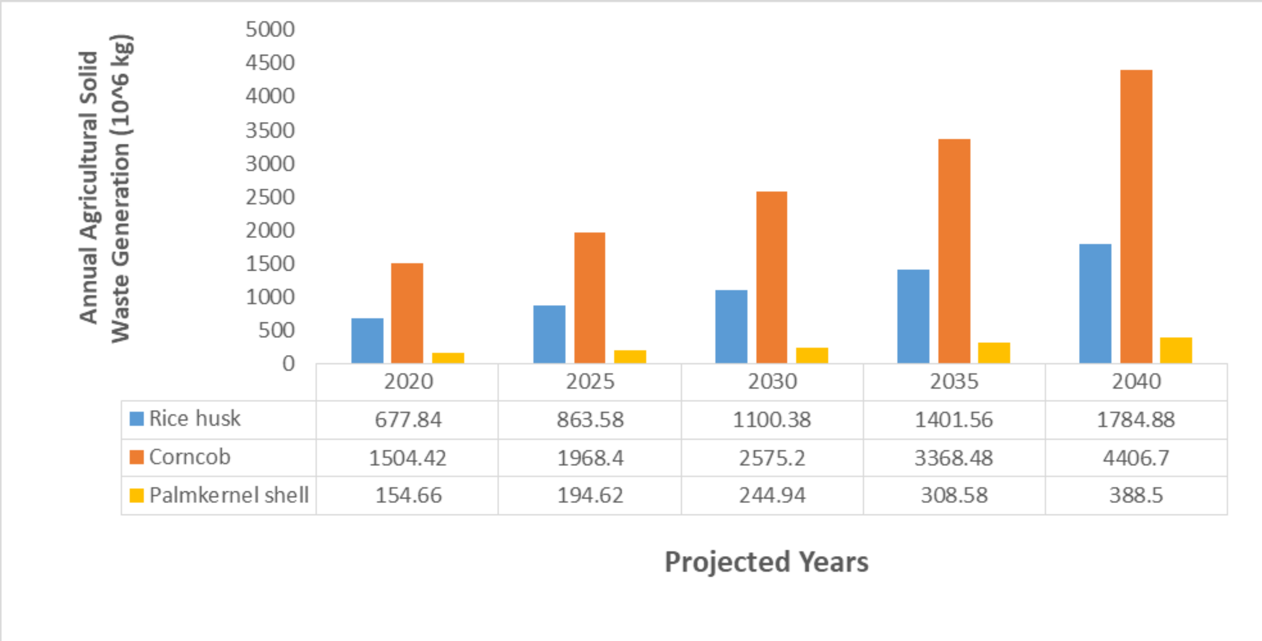


Fig.3. Projected annual waste production between 2020 and 2040

Table 8: Physico-chemical characteristics of selected ASWs

ASWs	**Proximate analysis % (Dry mass basis)**			**Ultimate analysis % (Dry mass basis)**					**% moisture content**	**HHV MJ/kg**
	Fixed carbon	Volatile carbon	ash	C	H	O	N	S		
RH	12.30± 5.77	66.46± 8.58	21.24 ±14.22	36.80 ± 4.64	5.21 ± 0.79	35.59 ± 11.23	0.59 ± 0.34	0.57 ± 0.50	6.98 ± 5.40	15.32 ± 0.94
CC	14.52 ± 6.92	83.44 ± 6.77	2.04± 0.75	42.91 ±0.74	5.77 ±0.11	48.18 ±0.48	0.51 ±0.18	0.59 ±0.65	10.36 ± 2.16	17.06 ± 0.24
PKS	11.76± 10.29	83.95±7.86	4.29± 2.71	43.85 ±4.09	5.27 ±0.48	46.23 ±2.54	0.33 ±0.23	0.03 ±0.03	9.1±2.07	17.48 ± 1.20

3.1.2. Annual electricity generation potential

The projected annual electricity production rate from 2020 to 2040 for the respective ASWs is presented in Fig. 4. It can be inferred from the figure that CC has the most potential for the generation of electricity via a combined pyrolysis/steam power plant system; having an average electricity generation potential of approximately 2077 GWh per year. On the other hand, RH has the potential to generate average annual electricity of about 854 GWh; while PKS showed the least potential of approximately 232 GWh of electricity per annum on average. As compared to others, the substantial electricity generation potential of CC could be rightly linked to its high waste generation potential, moderately high HHV as well as high bio-oil yield. Also, the figure depicted that a total of approximately 1800 GWh and 5060 GWh of electricity can be produced from the combined management of the ASWs in 2020 and 2040 respectively; with more than 60% of it from the use of CC. The average nominal plant size for handling each ASW is approximately 115 MW for RH, 280 MW for CC, and 31 MW for PKS. The upward trend of electricity production potential between the years of projection is attractive and for a nation that battles with a huge gap between electricity production and consumers' needs, the efficient utilization of these ASWs as suitable feedstock for waste-to-energy technologies should therefore be given utmost priority.

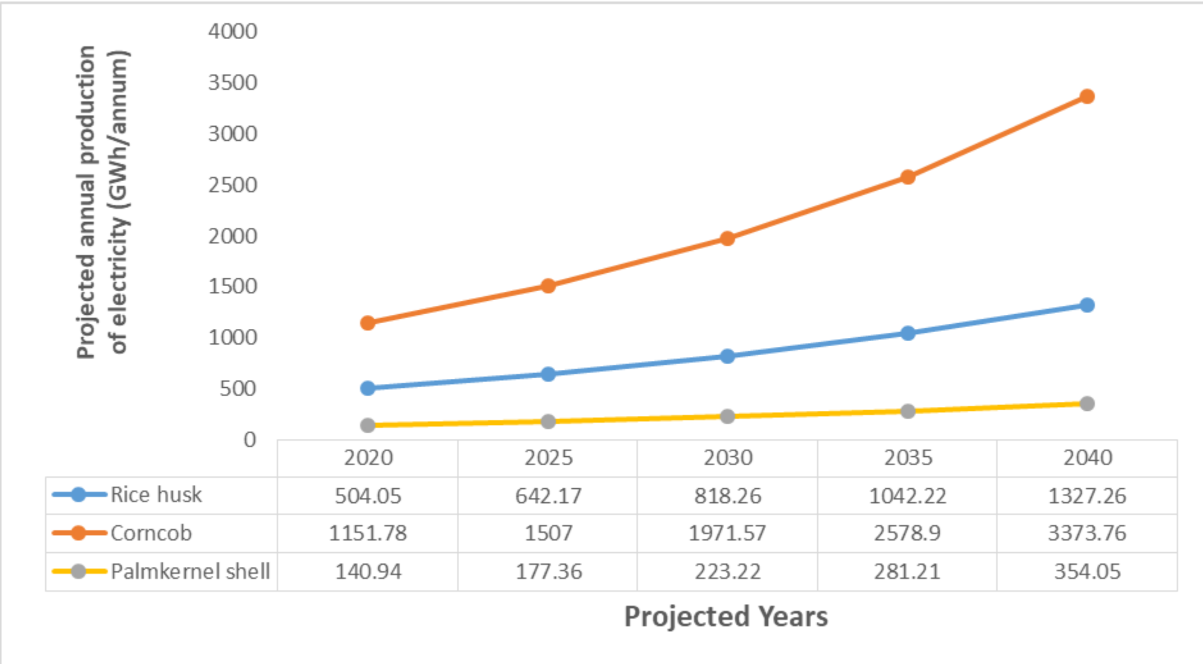


Fig.4. Annual electricity generation rate from ASWs (2020 – 2040)

3.1.3. Ecosystems impairment

The overall contributions to global warming, from the use of ASWs for electricity production, were obtained as 54.32, 55.88, and 54.54 kg CO_2 equivalent per volume of bio-oil consumed for RH, CC, and PKS respectively (see table 9). Among these alternative feedstocks, CC has the highest density (table 3) and thus tends to produce the greatest amount of CO_2 emission per unit volume of bio-oil when combusted for energy generation. The obtained GWP values were found to be lower than the GWP of 177 kg CO_2 equivalent/ m^3 bio-oil when cryptomeria residue was used as the basic raw material for bio-oil production and its subsequent use for energy generation [68]. The variation in the reported GWP values is due to the differences in the respective chosen waste-to-energy technology. In the present study, an auto-thermal pyrolysis conversion process was assumed; a technology that relies, for energy consumption, largely on the combustion of its constituent's products – pyrolysis gas and biochar – rather than the use of fossil fuels. The combustion of pyrolysis constituent's products are known to possess a zero net GWP [38], and hence the reason for the lower GWP values reported for the selected ASWs. The highest CO_2 reduction benefit of 1428.68 kg CO_2 equivalent/m^3 bio-oil was achieved when RH was used as the basic raw material, followed by 1428.46 kg CO_2 equivalent/m^3 bio-oil for PKS and 1427.12 kg CO_2 equivalent/m^3 bio-oil for CC.

Table 9: Environmental burdens associated with electricity production using ASWs.

Indicator	RH	CC	PKS
Characterization			
GWP (kg CO_2/m^3 bio-oil)	54.3204	55.8825	54.5399
AP (kg CO_2/m^3 bio-oil)	10.5534	10.8569	10.5961
Normalization analysis			
GWP	0.0041	0.0043	0.0042
AP	0.0934	0.0961	0.0938
Weighted evaluation			
GWP	0.0104	0.0107	0.0104
AP	0.9339	0.9608	0.9377

Equally, CC accounted for the highest acidification potential of about 10.86 kg SO_2 equivalent/ m^3 bio-oil as compared to approximately 10.55 and 10.60 g SO_2 equivalent/ m^3 bio-oil for RH and PKS respectively. Though CC has the least sulfur content among the alternative, its high AP is largely related to the high bio-oil density as compared to other ASWs (table 3). It is equally important to note that the use of fossil fuel during biomass collection and transportation stages has an immense effect on the quantity of SO_2 produced per m^3 bio-oil consumed for all the ASWs. The normalization analysis revealed GWP and AP values in the range of 0.0041 – 0.0043 and 0.0934 – 0.0961 respectively. Using weighted evaluation, the total environmental burden on the ecosystem was evaluated as approximately 0.94 Pt for RH, 0.96 Pt for CC, and 0.94 Pt for PKS, with AP accounting for more than 95% of the impacts in all scenarios. This is expected because when compared with GWP, AP has a higher weighting factor and it is considered to have a greater contribution to the damage of the ecosystem.

3.1.4. Economic benefits

The economic viability of the use of the selected ASWs for energy generation was evaluated using Eqs 15-28 and depicted in Fig. 5. The average annual production cost ranged from $ 0.110 – 0.180 per kilowatt of electricity produced; these values are within the range of values for several waste-to-energy technologies reported by Ogunjuyigbe et al. [53]. As evident from Fig. 5, RH, which has the lowest cost of producing bio-oil ($0.18 per kg), also has the lowest cost of electricity production as compared to others. The electricity production cost is known to be directly proportional to the operation and maintenance cost, which in turn depends largely on the cost of fuel; hence, with a constant fixed cost, the average annual production cost thus increases as the fuel cost increases and vice versa. Positive NPVs and average annual profit were observed for the various ASWs, with PKS and CC having the least and the greatest profitability potential respectively (see Fig. 5). CC generated the greatest amount of electricity, which increases the revenue relative to the production cost while PKS generated the least. High revenue relative to production cost indicates high profitability index and thus the best pathway for high NPV. This explains why RH, with moderate electricity generation potential and low production cost, has an NPV well above that of PKS.

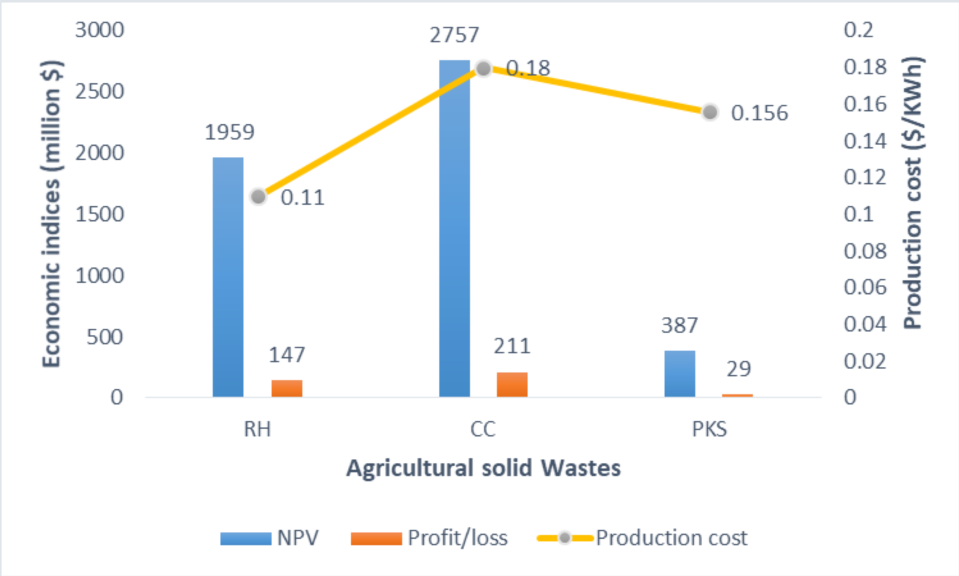
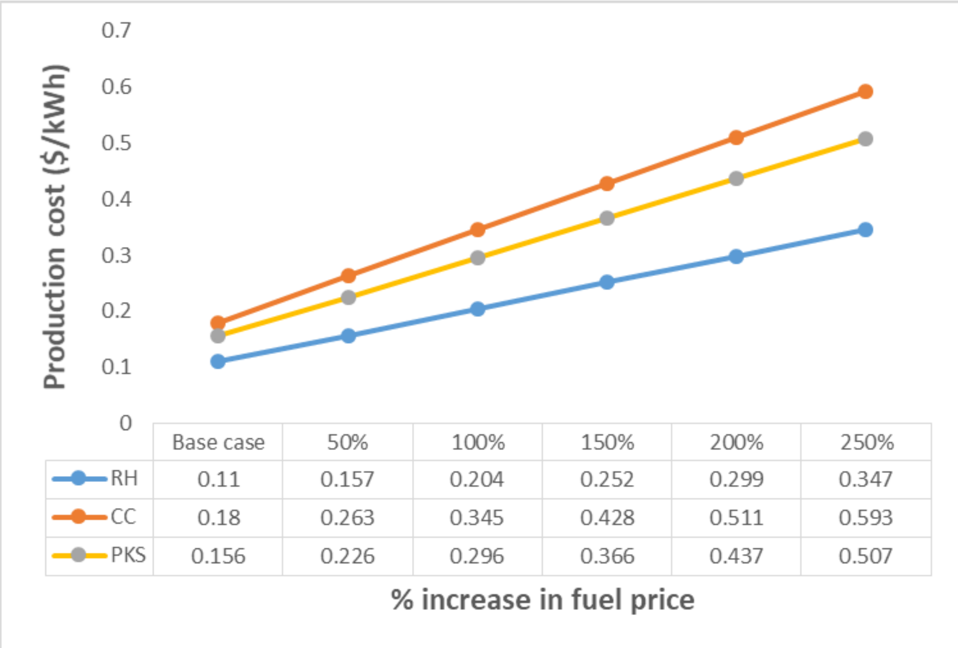


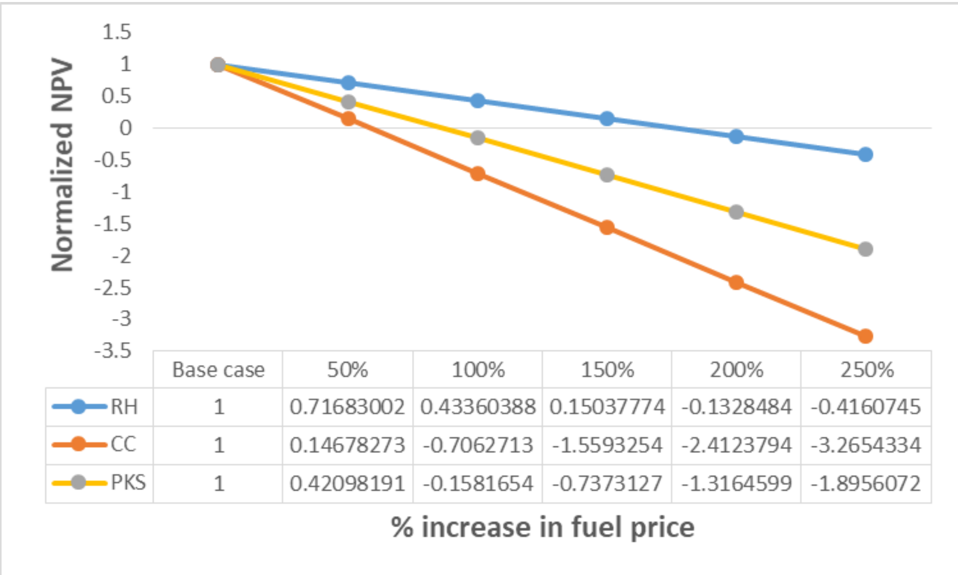
Fig.5. Summary of economic viability assessment

Bearing in mind that the cost of electricity is a function of the fuel cost; thus, an increase in the selling price of electricity will invariably lead to economic hardship for the consumer, especially in a developing nation like ours. Therefore, the volatility of the fuel cost cannot be ignored. The following assumptions in this study can lead to variation in the future cost of fuel: the commercialization of auto-thermal pyrolysis reactor is still in the developmental stage and cheap access to available raw materials for bio-oil production cannot be ascertained with certainty. Hence, a sensitivity analysis was carried out to ascertain the effect of the changes in the cost of fuel (bio-oil) on the NPV, production cost, and profit/loss. The effect of increasing the fuel cost from 50 – 250% is shown in Fig. 6 (a) – (c); to aid visualization the NPV and profit/loss values were normalized by the values of the base case for each ASW. As expected, in figure 6 (a), the production cost, for all ASWs, increases linearly with the percentage increase in fuel cost; which is as a result of the increase in the operation and maintenance cost.

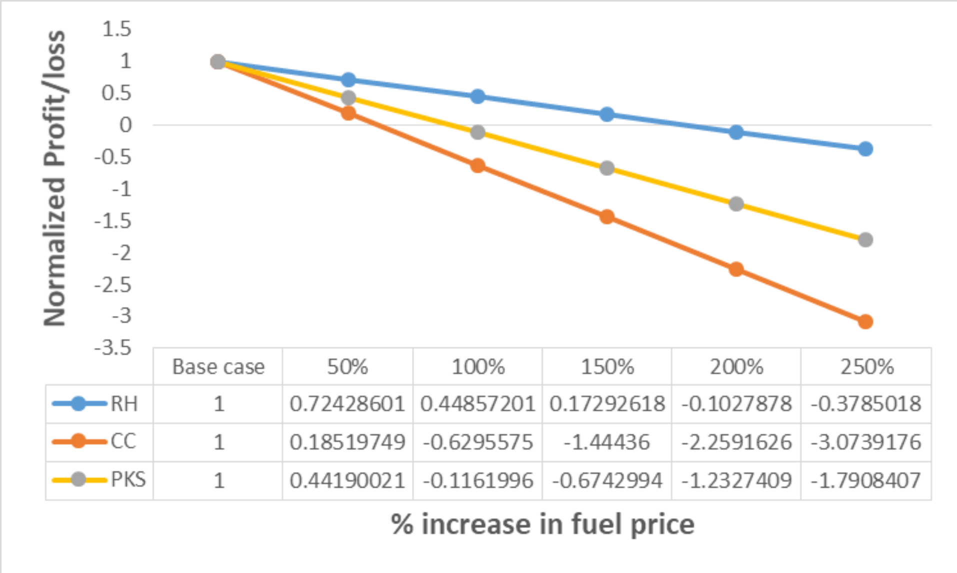
On the other hand, as shown in Figs. 6 (b) and (c), both NPV and average annual profit decrease linearly with the percentage increase in fuel cost. This is traceable to the fact that as fuel cost increases, the production cost increases relative to a constant revenue. Hence the profitability turns negative (loss) and the NPV reduces gradually. In both charts, the points at which the graph intersected the x-axis (the location of the least possible profitability potential) differ for each biomass; approximately 176% for RH, 58% for CC, and 86% for PKS. This phenomenon is due to the complex relationship between the bio-oil cost for the base cases and the average annual production cost; for example, as compared with others, RH with bio-cost of \$0.18 per kg allowed a percentage increase in more than three folds of its initial value. To therefore maintain a positive NPV for each ASW, a pessimistic bio-oil cost was established as \$ 0.496 per kg for RH, \$ 0.442 per kg for CC, and \$ 0.502 per kg for PKS.



a) Effect of % increase of fuel price on production cost



b) Effect of % increase of fuel price on NPV



c) Effect of % increase of fuel price on average annual profit/loss

Fig.6. Sensitivity analysis output

3.2 Result of TOPSIS assessment of alternatives

Table 10 summarizes the positive rating of alternative *i* to criterion j, as well as the corresponding weight of the individual criterion. The first three sets of criteria and the last two represent the monotonically increasing and monotonically decreasing preference respectively. As evident from Table 10, the electricity generation potential has the highest weight as compared to NPV which has the second-best weight; however, carbon reduction benefit and ecosystem impairment have the least weight among the selected criteria. Meanwhile, production cost weighs approximately 4 percent. Hence, within the scope and context of this study, electricity generation potential, NPV, and Production cost are the most feasible criteria for making a decision relating to the best biomass waste for electricity production in Nigeria. In terms of comparative preference ranking for each alternative; CC has the best rating for electricity generation potential and NPV. RH gave the best rating for carbon reduction benefit, production cost, and ecosystem impairment. On the other hand, PKS accounted for the second-best preference rating for carbon reduction benefit and ecosystem impairment; and the least preference rating in all other categories.

Table 10: Initial evaluation table for selecting the best alternative

Criteria	Alternatives			Weight
	RH	CC	PKS	
Electricity generation potential (GWh)	853.63	2077.35	232.24	0.5544
NPV (million $)	1959	2757	387	0.4057
Carbon reduction benefit kg CO_2 eq./m^3	1428.68	1427.12	1428.46	0.0002
Production cost ($/KWh)	0.110	0.180	0.156	0.0395
Ecosystem Impairment (Pt)	0.94	0.97	0.95	0.0002

The outcome of the assessment, as depicted in Table 11, revealed CC as the ASW with the highest potential for generating electricity with a comparative advantage over other ASWs in terms of technical, economic, and environmental indices. CC, unarguably, possessed the highest biomass waste generation potential with corresponding moderately high bio-oil yield leading to the highest electricity generation potential and economic returns. Similarly, RH possessed a moderately higher ranking score than PKS but lower than that of CC (which is less than 50% of that of CC), and this can be attributed to its high NPV, carbon reduction benefit, and production cost rankings. On the other hand, PKS showed the least attractiveness for electricity generation with a ranking score of less than 1.0%; as evident in table 10, PKS ranked low in almost all the chosen criteria. Hence, the choice of ASW for electricity production in Nigeria can thus be ranked as follows: CC – RH – PKS (table 11).

Table 11: Ranking of alternatives based on distance from ideal solutions

Alternatives	d_i^+	d_i^-	D_i^*%	Rank
RH	0.3151	0.2418	43.42	2
CC	0.0108	0.5337	98.02	1
PKS	0.5338	0.0038	0.70	3

4. CONCLUSION

To bridge the huge gap between electricity production and consumers' need in Nigeria, through alternative energy sources; the utilization of ASWs for electricity production was assessed. The considered ASWs have high energy contents, waste generation potential and are readily available for waste-to-energy conversion. It was established that the conversion of

ASWs to electricity via a combined pyrolysis- steam power plant technology seems attractive, sustainable, and economically feasible. The percentage increase in fuel cost was established to greatly affect the profitability potential and to maintain a positive NPV, a pessimistic bio-oil cost of $ 0.496 per kg, $ 0.442 per kg, and $ 0.502 per kg was established for RH, CC, and PKS respectively. Based on the selected performance indices, CC ranked as the ASW with the greatest potential for electricity generation as well as having a comparative advantage over other ASWs in terms of techno-economic and environmental indices. RH and PKS ranked second and third respectively.

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