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Original Research

Technical Analysis of Sawdust-to-Power: A Paradigm Shift in Waste Management in a Typical Developing Economy

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Abstract

The proper management of sawdust is critical to socioeconomic development. In this research, waste-to-energy has been proposed to utilize sawdust in selected timber markets in Port Harcourt, namely, Illoabuchi Timber Market, Marine Base Timber Market, and Mile 3 Timber Market. A quantitative approach has been taken to estimate the sawdust generation, energy potential, power generation capacities, and pollutant reduction of indiscriminate combustion of sawdust. The findings suggest that, annually, 171 ktons, 42 ktons and 12 ktons of sawdust, respectively, are generated at the Illoabuchi, Marine Base, and Mile 3 timber markets. Also, the annual energy potential of sawdust in each of these timber markets is within 206-3000 TJ, while power generation is within 2.65-42.56 MW. The proposed power generation can serve the energy needs of the timber markets estimated at 10.2 GWh, 2.7 GWh, and 0.7 GWh, respectively, for Illoabuchi, Marine Base, and Mile 3 timber markets, and also provide extra clean energy for their host communities, respectively, at 308.8 GWh, 76 GWh, and 19.2 GWh, annually. Additionally, the study shows the potential for the reduction of pollutants: particulate matter at 5.85-85.5 tons, carbon monoxide at 760.5-11102 tons, sulfur dioxide at 0.59-8.55 tons, and nitrogen oxide at 5.85-85.5 tons. This research can support policy decisions on properly utilizing sawdust in Nigeria and societies with similar waste management challenges.

Keywords

Sawdust generation; waste management; sustainable energy; energy potential; power generation; pollutants; socioeconomic development; distributed power

1. Introduction

Sawmilling is the largest sector of the wood-based industry in Nigeria. It is responsible for converting 80% of processed wood in the country [1]. The processes involved in wood conversion to usable products are responsible for the bulk of wood waste generation, including sawdust, barks, slabs, and shavings. It has been reported that wood waste generation in Nigeria is above 5.2 million tons, and sawdust generation from sawmills is over 1.8 million tons annually [2]. Properly managing sawdust waste is critical to Nigeria's socioeconomic development. Issues such as breeding sites for pests, poor health from illegal burning of sawdust, and loss of energy, amongst others, are predominant due to the mismanagement of sawdust in Nigeria. Okedere *et al.* [3] have shown that 96% of sawdust generation in Nigeria is lost to uncontrolled burning, resulting in particulate emissions. Again, it has been demonstrated that the unchecked combustion of sawdust is a significant cause of air pollutants in the city of Lagos, with the emissions of carbon monoxide estimated at 5625 tons.

In contrast, particulate matter, sulfur dioxide, and nitrogen oxide emissions were estimated at 43.3 ktos, 4.22 tons, and 43.3 tons, respectively 2016 [4]. Apart from that, during the rainy season, the heaps of sawdust attract wood deposit leachate with high intensity of dissolved organic matter that can stimulate the transition metals and toxic contaminants harmful to aquatic life [5]. The proper management of sawdust is a big challenge, considering that most of the timber markets in Nigeria strive to make profits, and waste extraction and subsequent disposal is a significant cost in timber trading. Nevertheless, the proper disposal of sawdust in an eco-friendly and economically sustainable manner allows for a safer and healthier working environment, which translates into increased quality, productivity, efficiency, and ease of doing business at reduced product cost [6]. When properly harnessed, sawdust can be used in different products: sawdust concrete, sawdust bricks, particleboards, and electricity generation. Given the health implications of particulate matter (PM) in the uncontrolled combustion of waste, Okedere *et al.* [3] have supported a waste-to-energy option for managing waste in Nigeria.

In the work of Rominiyi *et al.* [7], the potential use of sawdust in energy, manufacturing, and agricultural industries for the purpose of wealth creation was investigated. In the study, it was shown that an updraft gasifier can be used to produce producer gas whose constituents are mainly II oxide and hydrogen. In Rominiyi *et al.* [7], the sawdust was mixed with other biomass materials to form a pellet. The findings suggested that the pelletized sawdust can find valuable applications for power generation. Ali et al. [8] demonstrated the use of sawdust in biofuel production. The work proposed that sawdusts have higher and lower heating values of 13.98 and 11.65 MJ/kg, respectively, which are lesser than the heating values of fossil fuels. However, it was proposed that sawdust can serve as an excellent environmental substitute for fossil fuels. Hidayah et al. [9] investigated sawdust-fired steam power generation plants in another work. The study involved designing, analyzing, and testing voltage and duration of power usage in electrical loads. The findings proposed that the sawdust-fired power plant is able to provide a voltage of 1.3-2.0 V, with a lamp duration time of 10-15 minutes. Although sawdust particles were used in the study, the authors recommended that briquettes from sawdust waste would provide more sustainable power to meet people's increasing energy demands.

Biomass energy sources with carbon neutrality are reasonable solutions for mitigating climate change, a problem associated with fossil fuel power plants. In Fogarasi and Cormos [10], a blend of coal and sawdust co-firing electrical power generation was carried out at different concentrations of oxygen used in the combustion process. The study also investigated carbon capture and storage technology to mitigate against the harmful effects of coal-fired power plants. The performance of important parameters, such as specific CO_2 emissions, energy efficiency, and auxiliary power, were examined at the different oxygen concentrations. The findings of Fogarasi and Cormos [10] proposed that an increase in the concentration of combustion oxygen between 21.8 and 28.4% would boost the power plant's performance. However, a further increase in the concentration of combustion oxygen to 35% would reduce the efficiency of the power plant. Additionally, they proposed that carbon capture could reduce the plant's carbon dioxide emissions by 93%, similar to [11]. Nevertheless, Fogarasi and Cormos [10] proposed that at a 93% rate of carbon dioxide capture and 8% oxygen gas concentration, the power plant's performance decreases when the sawdust feedstock into the plant is increased.

Besides being used for onsite power generation, sawdust (and in general, biomass) is a good substitute for fossil power generation since it can be used to fuel existing fossil power plants without modifying the plant [12]. For instance, Fogarasi and Cormos [10] have proposed that if 10% of fossil-fired thermal power plants are replaced with biomass, there will be a reduction in carbon dioxide emissions by 500 million tons per year. Moreover, such power plant substitutes will reduce the enormous investment cost in renewable energy power generation technologies [10].

The global interest in energy transition suggests exploiting all plausible and sustainable ways to mitigate climate change, given the dire consequences of the average global temperature rising above 1.5 to 2 °C. Moreover, the 2022 catastrophic flooding event in Nigeria, which experts attributed to climate change, calls for urgent attention to transition away from polluting fuels. Utilizing the waste stream in sawmills for distributed power generation is a veritable means to address climate change and to meet the energy needs of sawmill facilities and their environs, and also to depressurize and decongest the grid power supply, especially in Nigeria where grid power supply is not able to cater for the clean energy needs of half of its population. This is particularly interesting as the cost of operating backup generators in Nigeria is at an all-time high, talking less of the environmental inconveniences of running backup generators. Thus, this study aims to investigate the technical feasibility of utilizing sawdust waste as input fuel in an organic Rankine cycle to (i) meet the electrical energy needs of selected timber markets, (ii) provide sustainable means of managing sawdust, and (iii) provide clean energy for the host community as a way of community development.

1.1 Novelty

Sawdust generation in timber markets in Port Harcourt is either left for scavengers or sold to low-income earners for cooking purposes. No deliberate effort has been made to harness these wastes in an environmentally friendly manner properly. This work is new, as it provides a more efficient means to harness sawdust through on-site power generation. Again, due to the cost of operating standby generators, the selected timber markets work at 11 hours daily. The proposed power generation can meet all the electricity needs of the market and increase the daily hours of operations, thus increasing throughput.

2. Materials and Methods

This research was carried out to estimate sawdust's energy and electricity generation potentials in selected timber markets in Port Harcourt. This is necessary to encourage the use of sawdust for electricity generation as a waste management option that can improve power supply in the timber markets and their hosting communities while mitigating the dangerous effects of indiscriminate and improper disposal and burning of waste. The research involves the following: (i) quantification of sawdust generation in the selected timber markets, (ii) estimation of the energy content (lower heating value and higher heating value) of sawdust, (iii) estimation of the annual energy potentials of sawdust generation, (iv) estimation of the electricity generation potential of sawdust using the organic Rankine cycle configuration, and (v) estimation of the abatement potential of pollutant gases from the uncontrolled burning of sawdust.

2.1 Materials

Mass balance was used to measure the size per bag of sawdust at the selected timber markets. Other data utilized in the work, such as representative values of physicochemical properties of sawdust (ultimate and proximate analysis) and pollutant emission factors, were sourced from the peer-reviewed literature [4, 13]. The pollutant emission factors were estimates from the study area's geographical region (Southern Nigeria).

2.2 Method

Three timber markets were investigated. The number of sawmills in each of the timber markets was obtained. The bags of sawdust generated per mill per day of operation were obtained. Thereafter, the mass of a pack of sawdust was determined using a mass balance. In each of the timber markets visited, it was noted that operations are carried out six times a week, Mondays through Saturdays, and for each day, the needs operated on an average of eleven hours, i.e., from 7 a.m. to 6 p.m. After obtaining relevant data from the timber markets, the research progressed into determining the energy potentials of sawdust in each need, estimating the electrical power from the sawmill markets, and choosing the potential for pollutant mitigation by the controlled power generation process.

2.3 Quantification of the Sawdust Generation in the Three Timber Markets

The timber markets were visited from 1st-3rd of August, 2022. The information obtained from the markets are shown in Table 1.

Table 1 Sawdust production in three timber markets in Port Harcourt.

Items	Units	Values
Illoabuchi Timber Market		
Total number of mills	Mills	103
Number of active mills	Mills	73
Average sawdust production	BPMPD	300
Size of sawdust per bag	kg	25
Weekly days of operation	days	6
Daily hours of operation	hrs	11
Marine Base Timber Market		
Total number of mills	Mills	25
Number of active mills	Mills	19
Average sawdust production (17 mills)	BPMPD	200
Average sawdust production (2 mills)	BPMPD	1000
Average size of sawdust per bag	kg	25
Weekly days of operation	days	6
Daily hours of operation	hrs	11
Mile 3 Timber Market		
Number of mills	Mills	5
Number of active mills	Mills	5
Average sawdust production	BPMPD	300
Size of sawdust per bag	kg	25
Weekly days of operation	days	6
Daily hours of operation	hrs	11

BPMPD means Bags per mill per day.

The information provided in Table 1 was used to calculate the annual sawdust generation for each of the timber markets and, after that, the estimation of the energy potentials of the waste generation. Equation 1 shows the yearly waste generation.

$$m_y = (NWD)(NAM)(BSM)(WSB)(10^{-3}) \tag{1}$$

Where m_y*(ton)* represents the amount of sawdust generation annually; *NWD(days)* represents the number of working days in a year; *NAM(mills)* represents the number of active mills; *BSM(bags)* represents bags of sawdust per mill per day; and *WSB(kg)* means the weight of sawdust per bag.

2.4 Estimation of Energy Potential of Sawdust in the Timber Markets

The amount of energy that can be produced from a sawdust sample depends on how much chemical energy is stored in it. Accordingly, the heating value (HV), also known as the calorific value (CV) of a fuel, is a measure of the energy content of the power. Therefore, the annual energy potential of the sawdust was estimated following the Equation presented in Equation (2).

$$EP = m_y \times LHV \tag{2}$$

Where EP(MJ) is the energy potential of sawdust; m_y (kg) is the mass of sawdust produced annually; and LHV(MJ/kg) is the lower heating value of sawdust. Table 1 estimates the annual production of sawdust in the selected timber markets.

The lower heating value (LHV) of sawdust is obtained using the waste equation model proposed by Arafat and Jijakli [14] and presented in Equation (3).

$$LHV = HHV - 9m_H h_{fg} \tag{3}$$

Where, *HHV(MJ/kg)* is the higher heating value of the feedstock (sawdust), m_H(-) is the mass fraction of hydrogen in the feedstock, and h_{fg}*(MJ/kg)* is the enthalpy of vaporization of water, given as 2.257 *(MJ/kg)*. The equation proposed by Mhilu obtains the HHV [15] and presented in Equation (4).

$$HHV = 0.3491C\% + 1.1783H\% + 0.1005S\% - 0.1034O\% - 0.0151N\% - 0.0211A\% \tag{4}$$

where, *H%, C%, S%* and *O%*, *N%*, *A%* are the percentage by mass of hydrogen, carbon, sulfur, oxygen, nitrogen, and ash, respectively, in the sawdust.

2.5 Estimation of Electricity Generation Potential

From the Energy Potentials (EP) of the timber markets obtained in Equation (2) and the average efficiency energy conversion technologies, the theoretical amount of electricity that can be produced was estimated using Equation (5):

$$EG_{Theo}(kWh) = EP \times \eta \tag{5}$$

Where *EP(MJ)* is the energy potential of the feedstock; *η%* is the energy conversion efficiency of the power plant; and EG_{Theo}*(kWh)* is the theoretical electricity generation.

2.5.1 Process Description of the Sawdust to Electricity Generation Plant

There are several power generation technologies that are suitable for the conversion of waste to electricity. This includes gas turbine plants, steam turbine plants, and organic Rankine cycles. However, in this work, an organic Rankine cycle is proposed. This is because the organic Rankine cycle has been proven to be very suited for distributed energy, especially when using low-grade thermal energy sources such as geothermal and agro-based. The gas turbine plant is categorized as a high-grade thermal power plant, while the steam turbine is classified as a medium-high-grade power generation technology.

Figure 1a shows an organic Rankine cycle that is driven by the combustion products of sawdust heat generation. The working fluid of the organic Rankine cycle is the Toluene. Toluene was considered because it is biodegradable and one of the most suitable working substances in organic Rankine power plants [16]. In Figure 1a, the working fluid is pumped from states 3 to 4 in an organic fluid pump designated as P, to the boiler's pressure, defined as heat recovery vapor generator (HRVG). The high-pressure fluid at state 4 is evaporated to state 5 in the heat recovery vapor generator. The evaporation is made possible by the flue gases of sawdust combustion, leaving the combustion chamber (CC) at state 1, and exiting the HRVG at state 2. The high enthalpy of Toluene working fluid leaving the HRVG at state five is thereafter expanded in an expander (Exp) to the pressure of the condenser (Cond) at state 6. After exiting the expander, the weak vapor is condensed in the vapor condenser to saturated liquid at state 3 to complete the organic Rankine power cycle, and the process is repeated. The condenser is water-cooled. Figure 1b presents the temperature-entropy diagram of the sawdust-driven organic Rankine cycle (ORC). The area under Figure 1b shows the net energy transferred to the working fluid for electrical power generation.

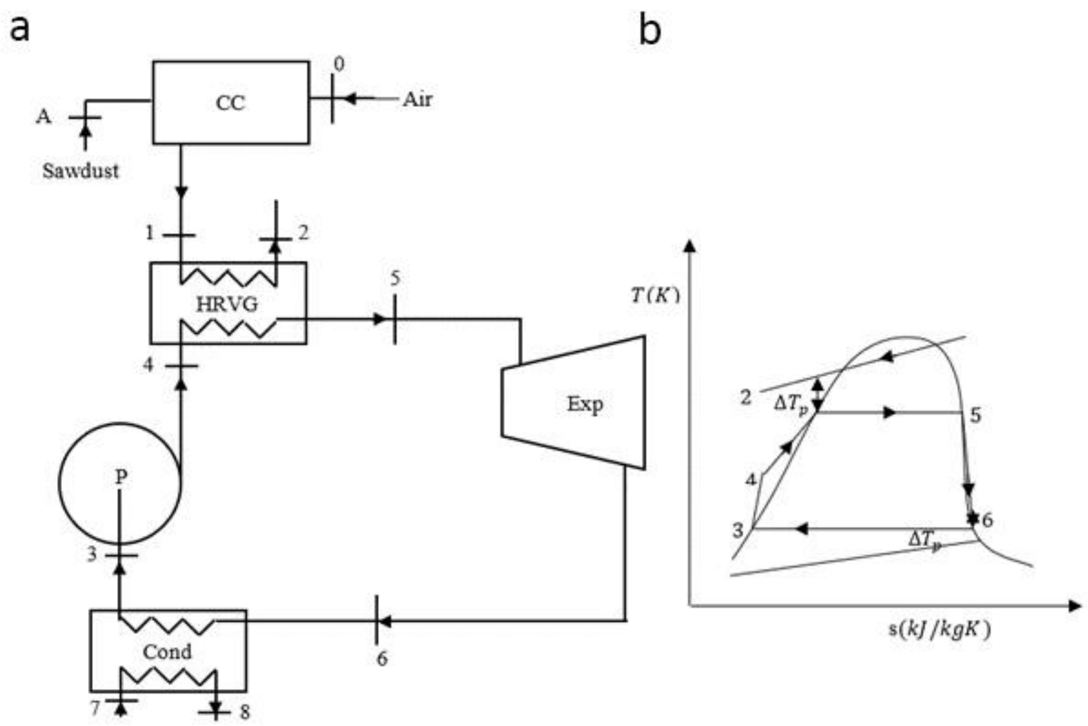

Figure 1 (a) Process diagram of sawdust powered organic Rankine cycle (b) T-s diagram of sawdust fired organic Rankine cycle.

2.5.2 Thermodynamics Modeling of the Proposed Plant

The electrical power plant cycle of Figure 1 comprises the sawdust combustion on one hand and an organic Rankine cycle on the other. The thermodynamic models of the organic Rankine cycle were developed similarly to the works of Dincer & Marc [17] and Lee [18]. The thermodynamic analysis is governed by the laws of conservation of mass and energy, given in Equations (6) and (7), respectively;

$$\sum_i \dot{m}_i = \sum_j \dot{m}_j \tag{6}$$

$$\dot{Q} - \dot{W} + \left(\sum_i \dot{E}_i - \sum_j \dot{E}_j\right) = 0 \tag{7}$$

Combustion of Sawdust. The sawdust composition is represented by hydrogen, oxygen, and carbon given by their molar fraction [19]. Considering that the formation of *CO* and NO_x in the combustion gases of sawdust is negligible, the reaction model of the combustion process is given in Equation (8).

$$C_xH_yO_z + \alpha_a\left[x + \frac{y}{4} - \frac{z}{2}\right]\left(O_2 + \frac{79}{21}N_2\right) \rightarrow xCO_2 + \frac{y}{2}H_2O + \left[x + \frac{y}{4} - \frac{z}{2}\right]\frac{79}{21}\alpha_a N_2 + (\alpha_a - 1)\left[x + \frac{y}{4} - \frac{z}{2}\right]O_2 \tag{8}$$

CxHyOz is the chemical formula of sawdust obtained by the method proposed by Chandrappa & Das (2012) [20]; x, y, and z are the number of carbon, hydrogen, and oxygen atoms, respectively; α_a(-) is excess air.

From the stoichiometric equivalent of Equation 8, fuel to air ratio is given as shown in Equation (9);

$$r_{f/a} = \frac{\dot{m}_{f,stoi}}{\dot{m}_{a,stoi}} = \frac{\bar{M}_f}{\alpha_a \frac{100}{21}\left(x + \frac{y}{4} - \frac{z}{2}\right)\bar{M}_a} \tag{9}$$

where, $\dot{m}_{f,stoi}$, $\dot{m}_{a,stoi}$ are the mass flow rates of sawdust (fuel) and air, respectively; $\bar{M}_f$ and $\bar{M}_a$ are the molar mass of fuel and air, respectively.

For actual combustion process, excess air over stoichiometric value is required given as Equation (10);

$$\alpha_a = 100\left(\frac{1}{r_{eq}} - 1\right) \tag{10}$$

Actual fuel-air ratio is given as;

$$r'_{f/a} = r_{eq} \times r_{f/a} \tag{11}$$

The adiabatic flame temperature of the sawdust combustion product is given as shown in Equation (12);

$$T_{ad} = (1 - \varphi)\left[T_R + \frac{r'_{f/a} \times LHV}{(1 + r'_{f/a})\bar{c}_{p,g}}\right] \tag{12}$$

where, r_{eq} *LHV*, $\bar{c}_{p,g}$ and φ (~0.15) are equivalent ratio, lower heating values of sawdust, average specific heat capacity of sawdust combustion flue gases, and factors accounting for dissociation of products at elevated temperatures, respectively.

The mass flow rate of flue gas is given as shown in Equation (13);

$$\dot{m}_g = \dot{m}_f \left[(1-\beta) + \frac{1}{r'_{f/a}} \right] \tag{13}$$

where, β(-) is the fraction of ash in sawdust and $\dot{m}_f \equiv \dot{m}_{f,stoi}$ (kg/s) is the mass flow rate of sawdust.

Energy Assessment of ORC. The organic Rankine cycle is made up of a heat recovery vapour generator (HRVG), vapor expander (Exp), condenser (Cond), and organic fluid pump (OFP). The rate of heat gain in the HRVG, $\dot{Q}_{HRVG}$*(kW),* rate of work transfer in the expander, $\dot{W}_{Exp}$*(kW),* rate of heat rejection in the condenser, $\dot{Q}_{Cond}$*(kW)* and power of OFP, $\dot{W}_{TC,OFP}$ *(kW)* are given respectively as in Equations (14), (15), (16), and (17).

$$\dot{Q}_{HRVG} = \dot{m}_t(h_5 - h_4) = \dot{m}_{fg}(h_1 - h_2) \tag{14}$$

$$\dot{W}_{Exp} = \dot{m}_t(h_5 - h_6) = \eta_e \dot{m}_t(h_5 - h_{6'}) \tag{15}$$

$$\dot{Q}_{Cond} = \dot{m}_t(h_6 - h_3) \tag{16}$$

$$\dot{W}_{OFP} = \eta_P \dot{m}_t(h_4 - h_3) = \frac{\dot{m}_t v_3 (P_e - P_k)}{\eta_P} \tag{17}$$

The power, $\dot{W}_{net}$*(kW)* of the organic Rankine cycle as well as its thermal efficiency, η(-) are given, respectively, as shown in Equations (18), and (19);

$$\dot{W}_{net} = \dot{W}_{Exp} - \dot{W}_{OFP} \tag{18}$$

$$\eta = \frac{\dot{W}_{net}}{\dot{m}_f LHV} \tag{19}$$

where $\dot{m}_t$*(kg/s)*, h_i*(kJ/kg)* are mass flow rate of toluene, state enthalpy values; v_3*(m³/kg)*, P_e*(kPa)* and P_k*(kPa)* are specific volume of toluene at the exit of condenser, evaporation pressure and condensation pressure respectively; η_e and η_p(-) are expander efficiency and pump efficiency respectively.

Annual energy generation from the proposed power plants is estimated by Equation (20).

$$E_y = (N)\left(\dot{W}_{net}\right) \tag{20}$$

where, E_y*(kWh)* is the annual energy generation by the proposed power plant; *N(hr)* is the total operational hours per year.

Annual energy consumption by the timber markets is shown in Equation (21).

$$EC_y = N\left(\sum_i^m P_{D30} + \sum_j^n P_{D60} \right) \tag{21}$$

where, $P_{D30}(kW)$ is the power supply of a 30 kVA generator, and $P_{D60}(kW)$ is the power supply of a 60 kVA generator; m is the number of sawmills using a 30 kVA generator, while n is the number of sawmills using a 60 kVA generator, and N is the total number of hours of sawmill operation per year; $EC_y(kWh)$ is the annual energy consumption by the timber market.

Excess energy generation for supply to the hosting community is presented in Equation (22).

$$E_{exc} = E_y - EC_y \tag{22}$$

Estimating the Amount of Pollutants that can be Avoided by Controlled Combustion. To determine the amount of air pollutant emissions (CO, SO_2, NO_x and particulate matter) from the open (uncontrolled) burning of sawdust, Equation (23) is applied.

$$E_i = A(EF_i)\varphi \tag{23}$$

where, $EF_i(kg_p/kg_w)$ is the emission factor of the *ith* pollutant; *i* represents PM_{10}, SO_2, NO_x, and *CO* for particulate matter, sulfur oxide, nitrogen oxide, and carbon monoxide; and $A(kg_w/yr)$ represent the activity level. These factors have been reported by Fakinle *et al.* [4] for Lagos state which has similar economy, and lie within the same geographical region (Southern Nigeria) with the study area; *p* represents pollutant; *w* represents waste (sawdust waste); φ(-) is the average rate of uncontrolled burning of sawdust in Nigeria, estimated as 96% [3]. The emissions arising from the indiscriminate combustion of sawdust estimated in Equation (23) can be avoided through a well-controlled combustion in the proposed organic Rankine power plant for sawdust conversion to power.

The sawdust generation data used in this work were obtained from three timber markets in Port Harcourt: Illoabuchi Timber Market, Marine Base Timber Market, and Mile 3 Timber Market. These data were presented in Table 1. However, the input data for the power plant are shown in Table 2. Different sizes of diesel generators, such as 30 kVA and 60 kVA, are in use in the timber markets. Estimates suggest that about 70% of the sawmills use the 60 kVA, while about 30% use the 30 kVA generators. This assumption was used to estimate the total energy consumption of the cluster of sawmills. Thus, providing a good information on the amount of excess energy that can be exported from the timber markets to serve some of the energy needs of the community where the timber markets are located.

Table 2 Input parameters.

Quantity	Symbol	Units	Value
Mass flow rate of fuel (sawdust)			
Illoabuchi Timber Market	$\dot{m}_f$	kg/s	15.2
Marine Base Timber Market	$\dot{m}_f$	kg/s	3.75
Mile 3 Timber Market	$\dot{m}_f$	kg/s	0.95
Operations of Sawmills			
Days of operation of mill per week	d_W	days	6
Daily hours of operation of mill	h_D	hr	11
Proximate and ultimate analysis*			
Proximate Analysis		**%**	
Moisture		3.07	

Volatiles		80.87	
Ash		3.38	
Fixed carbon		12.68	
Ultimate Analysis		**%**	
Carbon		46.09	
Oxygen		47.19	
Hydrogen		6.62	
Nitrogen		0.10	
Power plant parameters			
Percentage excess air	α_a	%	20
Expander isentropic efficiency	η_{ex}	%	90
Pump isentropic efficiency	η_P	%	90
Flue gas dissociation factor	φ	-	0.15
Ash fraction in fuel	β	-	0.034
Plant annual operating hours	τ_{op}	Hr	7500
Life of plant	n_{yrs}	Yr	20
Ambient temperature	T_0	K	298
Ambient pressure	P_0	kPa	101.325
Working fluid	-	-	Toluene
Evaporator temperature of ORC	T_5	K	580
Condenser temperature of ORC	T_3	K	363
Source of Power Supply to sawmills			
Diesel Generators	-	kVA	30, 60
Emission factors of pollutants			
Pollutants		Emission factor, kg_p/kg_w	
Particulate matter, PM_{10}		0.0005**	
Carbon monoxide, CO		0.065**	
Sulfur dioxide, SO_2		0.00005**	
Nitrogen oxide, NO_x		0.0005**	

*Varma and Mondal [13]; **estimates of pollutant [4] - within the same geographical region.

3. Results and Discussions

The results of this work are presented and discussed. The results include the energy potential of the sawdust production in the three timber markets. Also, the theoretical electrical energy of the sawdust-to-power is presented. Furthermore, the annual energy generation of the proposed organic Rankine power plant is introduced. The input data were fed into the model developed in Section 2 and then solved using the Engineering Equation Solver software. Table 3 shows the energy output of the timber markets. Table 4 presents the results of the thermodynamic performance of the timber markets. Table 5 suggests the possible annual pollutant abatement if a controlled ORC with end-of-pipe treatment is used instead of the present illegal open-to-air indiscriminate burning.

Table 3 Energy characterization of sawdust production at selected timber markets.

Quantity	Units	Values		
		Illoabuchi	Marine Base	Mile 3
Annual energy potential of sawdust	TJ	3000	739.7	205.5
Theoretical annual energy generation	TJ	1050	258.9	71.93
Annual energy generation of power plant	GWh	319.2	78.71	19.88
Annual energy consumption of sawmills	GWh	10.2	2.7	0.7

Table 4 Thermodynamics characteristics of proposed Sawdust power plant at selected timber markets.

Variables	Units	Values		
		Illoabuchi	Marine Base	Mile 3
Net power	MW	42.56	10.50	2.65
Thermal efficiency	%	15.94	15.94	15.94
Power requirement of pump	MW	1.52	0.37	0.09
Rate of heat transfer to toluene	MW	196.57	48.47	12.24
Power generation by ORC expander	MW	44.08	10.87	2.75
Rate of heat rejection by toluene	MW	154.01	37.97	9.59
Energy generation in sawdust combustion	MW	267.09	65.86	16.63

Table 5 Estimates of pollutants that can be avoided at the selected timber markets.

Pollutant	Total annual pollution, *tons/y*		
	Illoabuchi	Marine Base	Mile 3
Particulate matter, PM_{10}	85.5	21.06	5.85
Carbon monoxide, CO	11102	2738	760.5
Sulfur dioxide, SO_2	8.55	2.11	0.59
Nitrogen oxide, NO_x	85.5	21.06	5.85

Table 3 shows the selected timber markets' energy potential, theoretical energy, annual energy production, and annual energy consumption. Table 3 shows that the sawdust generation at Illoabuchi, Marine Base, and Mile 3, respectively, have the potential to generate 3000 TJ, 740 TJ, and 206 TJ of energy annually from sawdust feedstock of 171 ktons, 42.1 ktons, and 11.7 ktons. At an energy conversion efficiency of 35%, this can produce 1050 TJ, 259 TJ, and 72 TJ of energy annually at the Illoabuchi, Marine Base, and Mile 3 timber markets. However, from the proposed organic Rankine cycle power generation plant, 319 GWh, 79 GWh, and 20 GWh of electrical energy, respectively, is possible annually. Table 3 also suggests that 10.2 GWh, 2.7 GWh, and 0.7 GWh of energy is consumed by the total active sawmills at the Illoabuchi, Marine Base, and Mile 3 timber markets, respectively. This means that the energy production from the proposed power generation plants in the timber markets can meet the energy needs of the sawmills, and excess of 308.8 GWh, 76 GWh, and 19.2 GWh are available for possible distribution to the hosting communities of the Illoabuchi, Marine Base, and Mile 3 timber markets, respectively. Going by the African average electricity consumption per capita of 550 kWh, the excess electricity generation by the timber markets can meet the clean energy needs of 93600, 23000, and 5800 households, respectively, at Illoabuchi, Marine Base, and Mile 3, where each family has a total occupant of 5-6 persons.

Table 4 further shows the thermodynamic characteristics performance of the proposed organic Rankine cycle (ORC) plants. The table suggests that a net power output of 42.56 MW is possible from the sawdust generation, which has been tagged as waste at Illoabuchi Timber Market. Similarly, 10.5 MW and 2.65 MW are proposed at the Marine Base and Mile 3. The efficiency of the ORC power plant is 15.92%, which is higher than that of most organic Rankine cycle power generation plants, operating at 12% [21]. At this power generation capacity, the energy needs of the timber markets and their surrounding community can be met sustainably. This has the additional benefits of improved and reliable power generation with low environmental impact when compared with the heavily polluting diesel-fired generators that are being operated in the markets to either meet the entire energy needs of the sawmills or serve as backup to the epileptic grid-supplied electricity.

Furthermore, the proposed power generation can be operated as a decentralized power system with little to no transmission and distribution losses, unlike the centralized power generation system, which has about 15% of energy loss to transmission and distribution in Nigeria [22]. To attain the net power production in the selected timber markets, the turbine's expansion work rate is given as 44.1 MW, 10.9 MW, and 2.8 MW, respectively, for the proposed power plant at Illoabuchi, Marine Base, and Mile 3. In comparison, the work of pumping the working fluid (Toluene) to the desired pressure of fluid evaporation is given as 1.52 MW, 370 kW, and 90 kW, respectively. Also, the plants require input energy at 267.1 MW, 65.9 MW, and 16.6 MW, respectively, from the combustion of sawdust. The heat rejection rate from the proposed plants is 154 MW, 38 MW, and 9.6 MW, respectively.

The proposed power plants, operating at 7500 hours per year, can assist in increasing the hours of operations of the sawmills from 3432 hours per year, at 11 hours per day, 6 days per week, and 52 weeks per year. Increasing the hours of operation of the sawmills will increase the throughput of the mills and, with enhanced revenue generation, at no extra energy cost on the facilities.

Table 5 shows the amount of pollutants that can be abated when the illegal open burning of sawdust is replaced with well-coordinated sawdust to power generation proposed in this study. Table 5 shows that 85.5 tons of particulate matter, 11.1 ktons of carbon monoxide, 8.55 tons of sulfur dioxide, and 85.5 tons of nitrogen oxide can be abated annually when indiscriminate burning of sawdust at the Illoabuchi Timber Market is replaced with a well-controlled power generation plant. Corresponding values for the Marine Base and Mile 3 timber markets are 21.1 tons, 2738 tons, 2.1 tons, and 21.1 tons; and 5.9 tons, 761 tons, 0.59 tons, and 5.9 tons, respectively. Furthermore, although not considered in the present study, carbon dioxide emissions from the exhaust of the power plant can be easily tracked and captured through carbon capture and sequestration (CCS) technology. When a CCS technology is integrated correctly, carbon capture can serve as a means for oil recovery of depleted oil wells in the oil-abundant city of Port Harcourt [23].

Figure 2 shows how the net electrical power production and thermal efficiency vary with the outlet temperature of the combustion gases for the proposed power production plants at Illoabuchi Timber Market, Marine Base Market, and Mile 3 Timber Market. Figure 2 suggests that the higher the outlet gas temperature, the lower the plant's energy output and thermal efficiency. This is because at low outlet temperature, more energy is extracted from the combustion gases, resulting in high net power production, and at high temperature of the exiting gases, less power has been extracted - the total energy content of the outlet gases still remains untapped at high exiting gas temperature. This power and efficiency reduction trend is observed for the three selected timber markets. However, more power is generated in the Illoabuchi power plant, 43.8 MW at 90°C and 29.9 MW at 430°C since the waste generation is highest for this timber market and lowest for the Mile 3 Timber Market being 2.7 MW at 90°C and 1.9 MW at 430°C. The energy efficiency is the same for all timber markets.

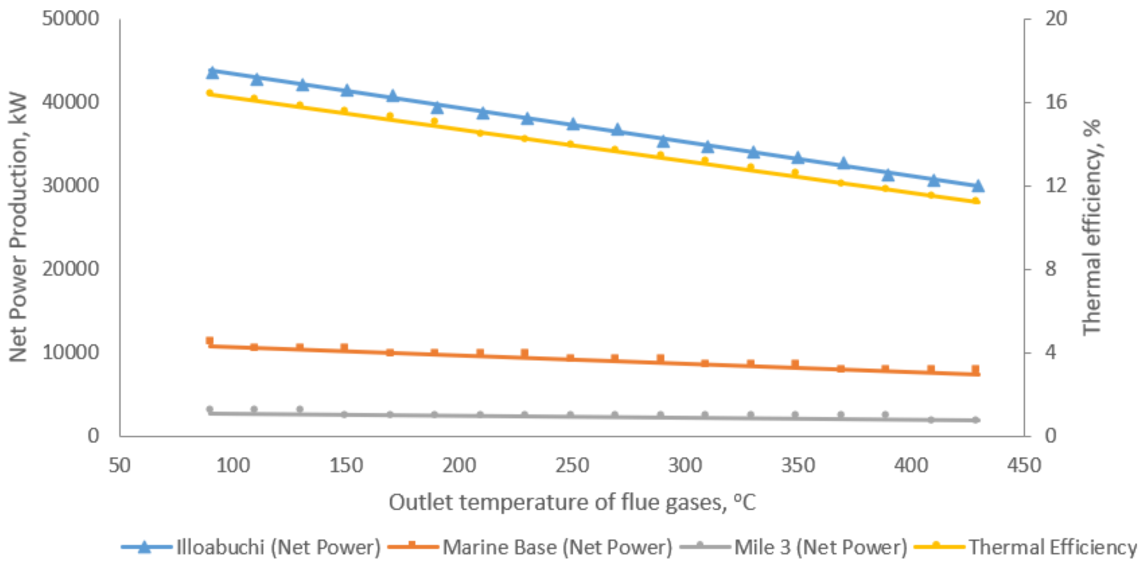

Figure 2 Variation of power production and efficiency with outlet temperature of combustion gases of sawdust.

4. Challenges Associated with Sawdust Energy Recovery

The benefits derived from the recovery of energy from sawdust through waste-to-power technology are numerous, including energy security, a clean environment, good health, and climate mitigation. Despite these benefits, different challenges can be associated with the process leading to the recovery of sound energy.

Firstly, sawdust collection at generation sites. The sawmill facilities under investigation do not have materials for the proper assembly, removal, and subsequent disposal of the generated sawdust. During a visit to one of the sites, it was observed that during the milling activities, sawdust is allowed to drop on the ground, which is not floored. While carrying out milling operations, millers often trample on the sawdust. This makes it very difficult to recover the sawdust for energy utilization. Thus, additional effort is required for sand separation from the sawdust particles to recover the sawdust.

Also, scavenging is another issue frequently encountered at sawdust generation sites. Since there is no proper collection, remover, and management of the generated sawdust, the waste is subjected to theft, especially by the low-income earners in the community, who come around to gather some of the sawdust that drops on the ground for use in sawdust cookstoves. In some cases, the millers trade the sawdust with the scavengers. The scavengers are primarily women or children. This group is often exposed to pollutants during the uncontrolled burning of these wastes for cooking.

Another challenge is the transportation of the sawdust to the point of utilization. These wastes are usually bulky, and riding to the end of use can pose some challenges. Carriers will require trucks with high running costs, especially if the point of utilization is far from the timber markets. Thus, onsite usage for decentralized power that can serve the electricity needs of the market and its immediate environment can help cushion the cost and emissions associated with the transportation of the waste to long distances.

5. Conclusion

Improper disposal of waste is a challenge that defaces the aesthetic look of most cities in Nigeria. There are also environmental and health factors to the indiscriminate disposal of waste - through illegal dumping on open sites, landfills, or uncontrolled burning. Sawdust is one such waste ravaging the vicinity of sawmills in Port Harcourt. When properly harnessed, sawdust can be used in several products, namely, sawdust concrete, sawdust bricks, particleboards, and even for electricity generation.

In this study, the energy recovery of sawdust through waste-to-power has been considered for the proper harnessing of sawdust generated at three timber markets in Port Harcourt, namely, Illoabuchi Timber Market, Marine Base Timber Market, and Mile 3 Timber Market. First, the amount of waste generation in these markets was estimated, thereafter, the energy contents of this waste (sawdust) were calculated for the three timber markets, an organic Rankine cycle was modeled to convert the chemical energy of sawdust waste to power, to meet the electrical energy needs of the market and its environs, while providing an alternative and better means to manage sawdust. The findings suggest that about 171, 42, and 11.7 ktons of sawdust are generated annually at Illoabuchi, Marine Base, and Mile 3 timber markets. These waste generation have the potential for 3000, 739.7, and 205.5 TJ of energy at the Illoabuchi, Marine Base, and Mile 3 timber markets, respectively. The results further suggest that organic Rankine power plants with 42.6, 10.5, and 2.7 MW capacity can be sited at the Illoabuchi, Marine Base, and Mile 3 timber markets. At these power capacities, the energy consumption of the timber markets estimated at 10.2, 2.7, and 0.7 GWh annually can be sustainably met, and extra energy of 308.8, 76, and 19.2 GWh can be exported to the hosting communities. In addition to meeting the energy needs, the proposed power plant has the potential for pollutant abatement or uncontrolled burning of sawdust. The study suggests that 5.85-85.5 tons of particulate matter, 760.5-11102 tons of carbon monoxide, 0.59-8.55 tons of sulfur dioxide, and 5.85-85.5 tons of nitrogen oxide can be mitigated at the timber markets under study if a well-coordinated ORC is installed.

The results also suggest that sawdust generation has enormous potential for clean energy generation at the timber markets, which will assist in eliminating the consumption of diesel in standby generators. Diesel standby generators not only increase the running costs of the sawmills but also pose serious environmental and health threats to the millers and the hosting communities.

The study recommends that the government formulate policies that adequately harness sawdust generation in Nigeria. At the same time, the Ministry of Environment should have a department or agency that precisely monitors the activities of sawmills throughout the country, seeing that it is one of the significant source of waste generation in Nigeria. Also, further study could be conducted to quantify the socio-environmental benefits of sawdust waste-to-energy power plants to drive further the need for proper harnessing of sawdust waste for power generation. This could be in the form of determining the carbon equivalent of the emissions of sawdust either in landfills or indiscriminately burning the trash.

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Author Contributions

Kesiena Owebor: Conceptualisation, Methodology, review and grammar check. Smith Orode Otuagoma: Writing - original draft and review. Ogheneakpobo Jonathan Eyenubo: Data analysis, review and editing. Arthur Gogo Uranta: Data curation, review and editing. Friday Erhimudia Ukrakpor: Data analysis, review and editing. Kesiena Ezewu: Review and editing. Ebimene Ezekiel Ebisine: Writing and editing.

Competing Interests

The authors have declared that no competing interests exist.

Abbreviations

BSM	Bags of sawdust per mill per day
CC	Combustion chamber
Cond	Condenser
EG_{Theo}	Theoretical energy generation
EP	Energy potential
Exp	Expander
HHV	Higher heating value
HRVG	Heat recovery vapour generator
LHV	Lower heating value
NAM	Number of active mills
NWD	Number of working days
WSB	Weight of sawdust per bag

Nomenclature

English Symbols

h_{fg}	Enthalpy of vaporisation of water, MJ/kg
$\bar{M}_a$	Molar mass of air, kg/kmol
$\bar{M}_f$	Molar mass of fuel, kg/kmol
m_y	Annual sawdust generation, kg
$r_{f/a}$	Fuel to air ratio
$\dot{W}_{net}$	Net power generation, kW
x	Number of atoms of carbon
y	Number of atoms of hydrogen
z	Number of atoms of oxygen

Greek Symbols

β Fraction of ash in sawdust
η Electricity generation efficiency, %
η_e Expander isentropic efficiency
η_P Pump isentropic efficiency, %
φ Dissociation factor, or rate of uncontrolled combustion of sawdust

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