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Yield and energy outputs analysis of sawdust biomass pyrolysis

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ABSTRACT

The use of alternative energy sources has become increasingly imperative due to the increasing demand for global energy and the depletion of fossil fuel reserves. Biomass stands as a key player in addressing both current and forthcoming energy challenges, serving as a promising solution to fulfill the heightened need for energy resources. This study focused on investigating the impact of temperature variation during the pyrolysis process on the resultant yield (syngas, bio-oil, biochar), as well as examining the physicochemical characteristics of energy, and exergy output. To accomplish this, a cylindrical pyrolysis reactor was specifically designed and utilized for the experimentation, employing wood sawdust with particle sizes ranging from 0.1 to 30 mm as the primary feedstock. The experimental investigations and subsequent thermodynamic analyses were conducted through a temperature range of 250 to 450 °C, employing a heating rate of 10 °C/min. The findings revealed a direct correlation between the increase in pyrolysis temperature and the enhanced output of bio-oil and syngas. Optimal yields were observed at different temperature values, with bio-oil peaking at 450 °C (55 %) and biochar at 250 °C (60 %). Furthermore, bio-oil yield notably reached 47 % with particle sizes below 0.1 mm. The viscosity of the produced bio-oil averaged between 2.06 and 3.55 mPa s, while the density consistently approximated 1.05 g/cm^3 across all cases. Detailed analyses including chemical and physical characteristics were conducted utilizing Fourier-transform infrared spectroscopy (FTIR), gas chromatography–mass spectrometry (GC–MS), field emission scanning electron microscopy (FESEM), and energy-dispersive X-ray spectroscopy (EDX). The observation and quantification of CO, H_2, CH_4, and CO_2 were part of the analytical process. This study shed light on the significance of temperature control in optimizing the output of valuable energy products from biomass pyrolysis, the potential for sustainable energy production, and the involved interplay of variables influencing the process.

1. Introduction

Solid waste management and the energy crisis are the major issues challenged by humanity [1–3]. The worldwide interest in exploring possible renewable energy sources has increased. Fossil resource consumption and fuel production both negatively affect the environment and ought to be reduced [4–7]. Diversifying energy sources is necessary because it enables a decrease in reliance on fossil fuels, which reduces anthropogenic greenhouse gas releases and the damaging consequences on the environment [8–10]. Coal, oil, and natural gas have been considered the foremost conventional energy resources over the last decades. As a biodegradable, renewable, and biocompatible resource, biomass can be used to generate energy, chemicals, fuels, and extra products for industrial uses [11]. Subsequently, the quantity of CO_2 emitted through combustion is equivalent to the quantity absorbed by trees and plants throughout their lives, biomass is regarded as an energy carbon–neutral source. Many different types of biomass can be found, including forest, crop residue, food waste, waste from food preparation, wood, animal waste, industrial biomass waste, and municipal waste [12]. A prevalent and plentiful biomass that can be converted into bio-oil rapidly through pyrolysis is forest waste [13–15]. For centuries, there was not much interest in forestry wastes. However, in recent decades,

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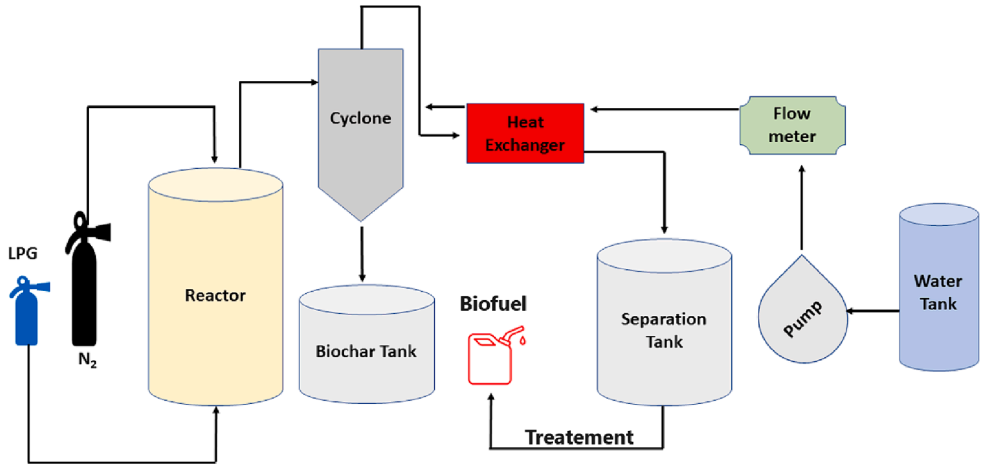


Fig. 1. Sawdust pyrolysis reactor.

the energy community has been concerned about the wastes' potential value and they have begun to be recognized as useful feedstock for energy transformation. However, it is important to take into consideration several factors such as availability, process efficiency, and environmental impact. These days, a lot of nations are interested in turning wood waste into biofuels [16,17]. Three substances make up almost all of the mass of all woody biomass: lignin, hemicellulose, and cellulose. The remaining biomass is made up of extractives such as resins, oil, and ash [18].

Even though the circular economy may benefit from the use of such feedstock by recycling treated wastes and nutrients as secondary resources [19,20]. Moreover, pyrolysis is considered an effective transformation procedure that transforms biomass substances into precious biofuels even in the absence of air [21,22]. The three forms of biofuel yield are char, oil, and gas, and the parameters of the reaction have a significant impact on both their energy content and yield [23,24]. Agro-residues are thermally degraded into renewable fuel during pyrolysis in an oxygen-free atmosphere. The H_2, CO, CO_2, C_6H_6, and CH_4 gases are produced during pyrolysis and can be used to heat the pyrolysis procedure. Additionally, it can be utilized to create power in a multiplicity of devices, including turbines, gas engines, and steam cycles [25]. Thermal pyrolysis is the conventionally used method for transforming biomass into high-quality bio-oil since it is both cost-effective and environmentally suitable [26].

Biomass pyrolysis can be arranged into three major classifications: flash pyrolysis, slow (conventional) pyrolysis, and quick pyrolysis according to the heating percentage and solid residence duration. The bulk of the biomass is lignocellulosic owing to its extended residence time, low temperature, and compatibility of several different particle sizes (5–50 mm). Lignocellulosic is thermally decomposed and it progresses at a quite minimal heating value with adequate time for depolymerization reactions to boost the solid products [27]. In contrast, rapid pyrolysis is the procedure for quick decomposition of biomass to mainly vapors and aerosols, with some charcoal and gas. After cooling and condensation, a dark brown homogeneous mobile liquid is produced, with its heating value being roughly half that of regular fuel oil. Most low-ash biomass diets result in high liquid yields. The temperature of the pyrolysis reaction is carefully regulated to be about 500 °C to increase the liquid output for the majority of biomass [28]. When utilizing HTC alone with a pyrolysis temperature of 450 °C, the H_2 to CO molar ratio attains its highest value of 9.2 [29]. In another study, agriculture biomass pyrolysis was utilized for gas production. The pyrolysis procedure was performed at a temperature between 300 and 600 °C under a nitrogen atmosphere. At 600 °C, the tar and gas percentages were 56.9 % and 19.0 %, respectively. The maximum quantities of valuable gases, including hydrogen and methane, were found in the resultant gas which was accumulated when the rector heated up to 600 °C. The quality of the resultant gas was improved with temperature [30].

Sawdust pyrolysis was conducted to produce bio-oil and biochar using a cycling reactor. Sawdust was subjected to pyrolysis at temperatures ranging from 400 °C to 600 °C, with the optimal temperature determined to be 500 °C. The resulting yields were reported as 26.5 %, 34.9 %, and 38.6 % by weight for syngas, bio-oil, and biochar, respectively. Additionally, a vertically moving cycling reactor was utilized to scale up the pyrolysis reaction. The reactor capacity was 15 kg/hr and kept at 500 °C. The resultant outputs were 31.36, 41.05, and 27.59 wt% for syngas, bio-oil, and bio-char, respectively [31]. In the procedure of an auger pyrolysis reactor, sawdust from the Acacia wood processing industry is used to generate bio-oil and biochar. The enhanced heating quantity of sawdust feedstock, carbon content, ash concentration, and volatile content were 19.33 MJ/kg, 47.40 wt%, 1.13 wt%, and 68.46, respectively. The pyrolysis studies were conducted in the temperature range of 400 to 600 °C by keeping material residence time, conveyer rotation speed, nitrogen flow rate, biomass particle size, and biomass feeding rate of 5 min, 4.5 rpm, 300 cm^3/min, 0.5–1.0 mm, and 180 g/h, respectively. For biochar, bio-oil, and non-condensable gas, the final yields were ranging from 29.72 to 51.85 wt%, 29.40–45.10 wt%, and 29.40–45.10 wt%, respectively [32].

The furniture industry generates significant quantities of sawdust, which have not been optimally utilized. This study aims to assess the optimal conditions for utilizing this industrial waste in fuel production, thereby promoting sustainability within the industry. To achieve this goal, a pyrolysis reactor was designed and installed. The waste wood sawdust was processed to yield bio-oil, charcoal, and syngas. Both thermodynamic analysis and experimental investigations were conducted to evaluate the performance of the reactor.

2. Materials and methods

2.1. Materials

The wood sawdust is a byproduct of a furniture manufacturing factory in Egypt. Therefore, it can be served as a biomass source. It consisted of a mixture of various wood types, including European Oak, American Oak, Bamboo, Beech, Iroko, Cherry, and Mahogany. These woods were sourced from countries such as Sweden, Finland, Croatia, China, and Indonesia. The moisture content of the wood sawdust ranged from 10 % to 22 % by weight. Prior to utilization, the sawdust was dried at 70 °C for three hours to lower its moisture content up to 6 %.

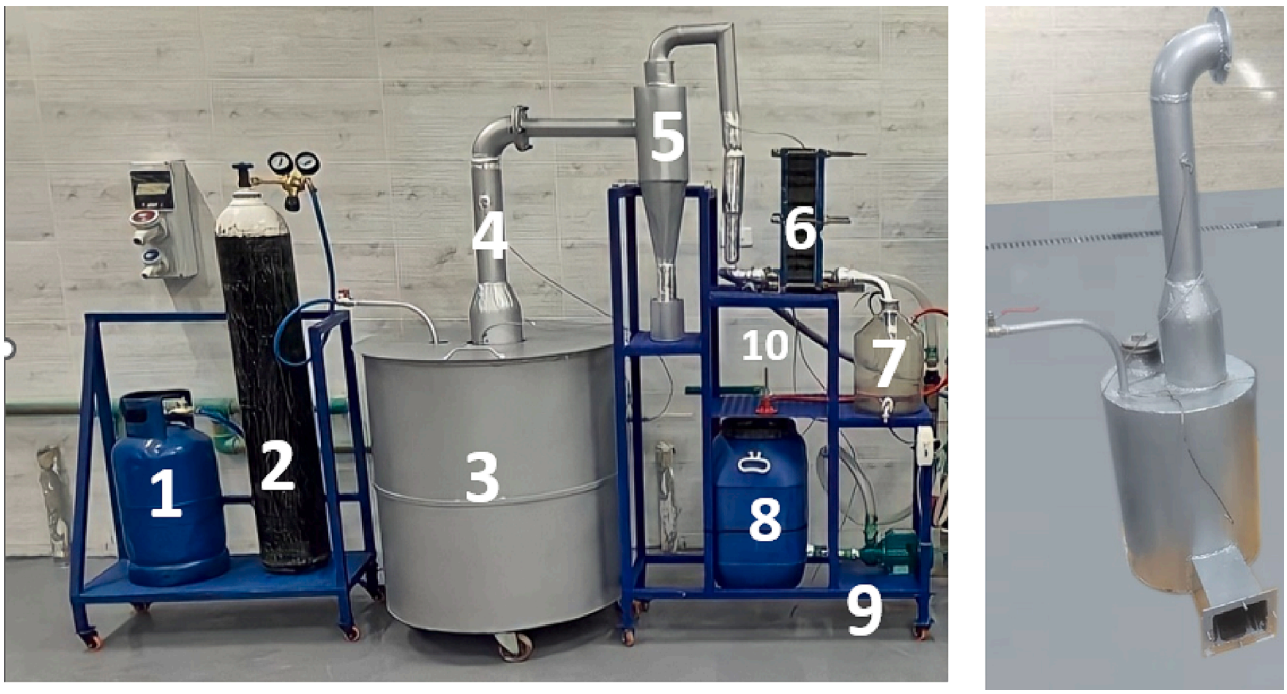


Fig. 2. Experimental setup of the pyrolysis unit.

2.2. Sawdust characterization

Evaluating the ash substances (ASTM E1755), volatile substances (ASTM D3173), and moisture content (ASTM D3173), the examination of biochar and sawdust were studied according to ASTM D3175. The fixed carbon fraction was determined using the variance between their masses. An elemental analyzer was utilized to reveal the element content of the feedstock and the biochar (Elementar Vario EL III). The biomass oxygen content was measured by the mass differential. The feedstock and biochar were measured via an IKA C200 bomb calorimeter to obtain the maximum heating value (ASTM D5865). The most important element in biomass fuels is oxygen. To estimate the weight of oxygen content, subtract the concentrations of the remaining components (H, N, and C), in addition to the dry fuel, from 100.

2.3. Experimental method

The sawdust pyrolysis reactor is shown in Fig. 1. In the proposed reactor with nitrogen present, wood sawdust was slowly pyrolyzed five times at temperatures of 250, 300, 350, 400, and 450 °C. Based on the findings of the GC–MS investigation, there is a considerable disintegration of the wood sawdust where the temperature ranged between 250 and 450 °C. As a result, the current study was conducted at temperatures between 250 and 450 °C. Additionally, as recommended in the literature [33,34], all tests were conducted at a heating rate of 10 °C min^{-1} and a residence time of 15 min. The PLC was used to regulate the required temperature, heating rate, pyrolysis process, and retention period to produce the appropriate output.

A reactor held 1.0 kg of air-dried wood sawdust for each experiment. To heat the biomass to the necessary temperature in the unit, liquefied petroleum gas (LPG) was used. The reactor was made of solid iron sheet tubing that has a 400 mm diameter and a 650 mm length, as illustrated in Fig. 2a and 2b. Utilizing a heat exchanger from a type (flat plate) condensing unit, organic vapor was condensed at a temperature of 20 °C. The tube features a sealed end and a flange on opposite ends. To distinguish between condensable and non-condensable gases, the syngas was collected from the reactor's side and transported into the condensing unit.

The 500 ml glass tube used to collect the produced bio-oil was then examined to determine its constituent elements and other chemical components. Utilizing a gas analyzer, syngas components were measured straight from the syngas output. The yield was calculated after the experiment by collecting the biochar from the reactor and measuring its weight. The distribution of product yield was calculated using equations (1–3).

$$Bio-oil\ yield(\%) = \frac{Mass\ of\ \ Bio-oil}{Mass\ of\ \ Biomass} \times 100 \quad (1)$$

$$Biochar\ yield(\%) = \frac{Mass\ of\ Biochar}{Mass\ of\ Biomass} \times 100 \quad (2)$$

$$Masslosses(\%) = [100 - (biocharyield\% + bio-oilyield\% + gasyield\%)] \quad (3)$$

3. Thermodynamic analysis of the pyrolysis procedure

3.1. Mass balance

The mass balancing was brought out in order to meet the biomass pyrolysis process' requirement for mass conservation. By balancing the input and output of the reactor with the pyrolysis procedure, the mass balance was accomplished. Biomass served as the feedstock for the reactor, yielding charcoal, bio-oil, and non-condensable syngas as products [35]. The fundamental mass balance equation for the pyrolysis procedure is given by equation (4).

$$M_{biomass} = M_{biochar} + M_{bio-oil} + M_{gas} + M_{loss} \quad (4)$$

The total mass ratio of production to whole mass intake represents the closure of the mass balance (MBC).

3.2. Energy and exergy analysis

Equation (5) represents the energy equilibrium of the pyrolysis process.

$$E_{biomass} + E_{heat} = E_{biochar} + E_{bio-oil} + E_{gas}E_{loss} \quad (5)$$

Where E_{heat} and $E_{biomass}$ are the heat energy input and biomass energy needed for the pyrolysis mechanism, respectively. The acronyms for the created energy by gas, bio-oil, and char are E_{gas}, $E_{bio\text{-}oil}$, and $E_{biochar}$. The biomass's real energy is given by Eq. (6):

$$E_{biomass} = M_{biomass} \times LHV_{biomass} \tag{6}$$

Where $M_{biomass}$ and $LHV_{biomass}$ indicate both the use of biomass and its lower heating value, respectively.

Eq. (7) is used to estimate the biomass LHV [24,36]:

$$LHV = HHV - \frac{9 \times H\% \times h_{fg}}{100} \tag{7}$$

The heat energy using LPG for heating throughout the pyrolysis procedure was addressed by Eq. (8) and (9) [34]. The heating rate for bio-oil (Eq. (8) and char (Eq. (9) was determined.

$$E_{pyrp-oil} = M_{pyro-oil} \times LHV_{pyro-oil} + M_{pyro-oil} \times C_{p,pyro-oil} \tag{8}$$

$$E_{char} = M_{char} \times LHV_{char} + M_{char} \times C_{p,char} \tag{9}$$

The bio-oil and char-specific heat was taken into consideration at 1.59 kJ $kg^{-1}K^{-1}$, and 2.49 kJ $kg^{-1}K^{-1}$, respectively [37]. Energy from physical sources makes up the syngas energy rate is given by (Eq. (10):

$$E_{gas} = E_{ph} + E_{ch} \tag{10}$$

The syngas physical power rate was calculated via specific enthalpy (kJ kg^{-1}) and the syngas (in kg) using Eq. (11) [38]:

$$E_{ph=} M_{gas} \times h_{gas} \tag{11}$$

The syngas-specific enthalpy was calculated using Eq. (12) combining the enthalpies and mole percentages of gases such as CO, H_2, CO_2, and CH_4.

$$h_{gas} = \sum_{i=1}^{n} h_{0i} + y_i \times C_{pi} dT \tag{12}$$

Where h_{0i} and h_{gas} indicate enthalpy at the reference temperature and specific temperature, respectively.. y_i and C_{pi} represent the mole percentage of syngas composition, and the specific heat of different gas elements, respectively. Eq. (13) was used to calculate the specific capacity of heat

$$C_p = A + BT + CT^2 + DT^3 + ET^4 \tag{13}$$

The constants are described in the literature [39], whereas T is the temperature of syngas in K. The energy content of the pyrolysis gas was determined using Eq.(14).

$$E_{ch} = M_{gas} \times \frac{LHV_{gas}}{\rho_{gas}} \tag{14}$$

To calculate the LHV of syngas, Eq. (15) was applied [40]

$$LHV_{gas}\left(MJNm^{-3}\right) = (11.2 \times H_2\%) + (13.1 \times CO\%) + (37.1 \times CH_4\%) \tag{15}$$

The subsequent equation was used to calculate the energy output (16).

$$EnergyYield(\%) = \frac{M_{product} \times LHV_{product}}{M_{biomass} \times LHV_{biomass}} \tag{16}$$

Where M product is the mass output percentage of the product. Eq. (17) can also be utilized to determine the energy efficiency (η) of the pyrolysis process

$$\eta(\%) = \frac{E_{char} + E_{bio-oil} + E_{gas}}{E_{biomass} + E_{pyro} + E_{heat}} \tag{17}$$

Exergy represents the maximum potential work that can be extracted from a material or system as it reaches equilibrium with its surroundings, as defined by the second law of thermodynamics[41].

In the pyrolysis technique, all fluids were entering and departing streams, and the assumed heat transfer boundary was at a reference conditions [42].

$$E_x = \beta \times M \times LHV \tag{18}$$

Where the correspondence factor in Eq. (18) is β calculated via Eqs. (19)–(21) [43,44].

$$\beta_{biomass} = \frac{1.0412 + 0.2160\frac{H}{C} - 0.2499\frac{O}{C}\left[1 + 0.7884\frac{H}{C}\right] + 0.0450\frac{N}{C}}{1 - 0.3035\frac{O}{C}} \tag{19}$$

$$\beta_{biochar} = 1.0437 + 0.1896\frac{H}{C} + 0.0617\frac{O}{C} + 0.0428\frac{N}{C} \tag{20}$$

$$\beta_{bio-oil} = 1.0401 + 0.1728\frac{H}{C} + 0.0432\frac{O}{C} + 0.02169\frac{S}{C}\left(1 - 2.0628\frac{O}{C}\right) \tag{21}$$

Eq. (22) [45] was was used to calculate the exergy associated with the heat required for the pyrolysis process.

$$E_{xpyro} = E_{pyro} \times \left(1 - \frac{T_0}{T_{pyro}}\right) \tag{22}$$

Eq. (23) [46] may be used to calculate exergy efficiency.

$$\tilde{N}^{\circ} = \frac{E_{xchar} + E_{xoil} + E_{xgas}}{E_{xbiomass} + E_{xpyro}} \tag{23}$$

3.3. Sustainability analysis

Sustainability analysis is critical in every industry operation. It limits the process of societal environmental effects. It also adresses economic progress, societal harmony, and environmental harmony [35,46]. The sustainability index (SI) is a metric used to assess sustainability based on energy efficiency. The sustainability index evaluates the unit's sustainability in light of the fuel sources and the rising SI value will be advantageous. Several environmental variables may be utilized to assess the sustainability of the pyrolysis process [28]. The sustainability index is given by Eq.(24) [47].

$$SustainablityIndex(SI) = \frac{1}{1 - \eta_{ex}} \tag{24}$$

Where η_{ex} denotes the exergy adeptness as defined by Eq (24). Calculating the system's prospective advancements also indicated the possibility for improvement [47,48].

It calculates the lost exergy and exergy efficiency of the processt as given by Eq. (25).

$$Improvementpotential(IP) = \left[1 - \left(\frac{E_{x,D}}{E_{x,in}}\right)\right] E_{x,D} \tag{25}$$

Where $E_{x,D,}$ and $E_{x,in}$ are the values of the waste exergy, and the total potential exergy of inputs [46,47].

The environmental impact factor (f_{env}) is given by Eq. (26) [48]. It was utilized to estimate the ecological effect of waste exergy.

$$f_{env} = E_{wastedexergy} \times \frac{1}{\eta_{ex}} \tag{26}$$

4. GC–MS chromatographic analysis

Chromatographic analysis was performed via GC–MS device (Agilent Technologies 7890B GC Systems combined with 5977A Mass Selective

Table 1
Elemental, proximate content, and heating value of biochar and WSD.

Characteristics	Sawdust	Biochar
Proximate composition (%)		
Moisture	6.70	1.13
Volatile matter	73.4	21.55
Fixed carbon*	14.70	64.77
Ash	5.20	12.55
Elemental composition (%)		
C	40.30	64.40
H	5.37	3.03
N	1.28	0.69
O*	100-[C%+H%+N%] = 53.05	31.88
O/C molar proportion	1.316	0.40
H/C molar proportion	0.133	0.49
Empirical formula	$CH_{1.83}O_{0.75}N_{0.009}$	$CH_{0.54}O_{0.38}N_{0.01}$
HHV (Mj/kg)	18.24	21.98

*By difference.

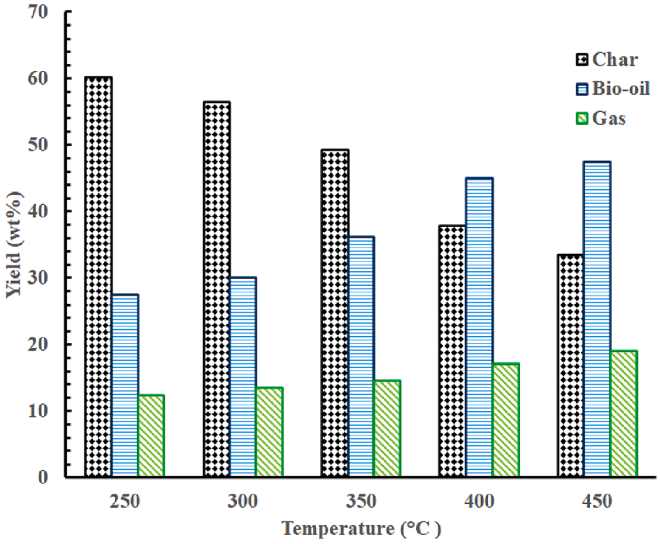


Fig. 3. Temperature influence on gas, char, and bio-oil pyrolysis yield.

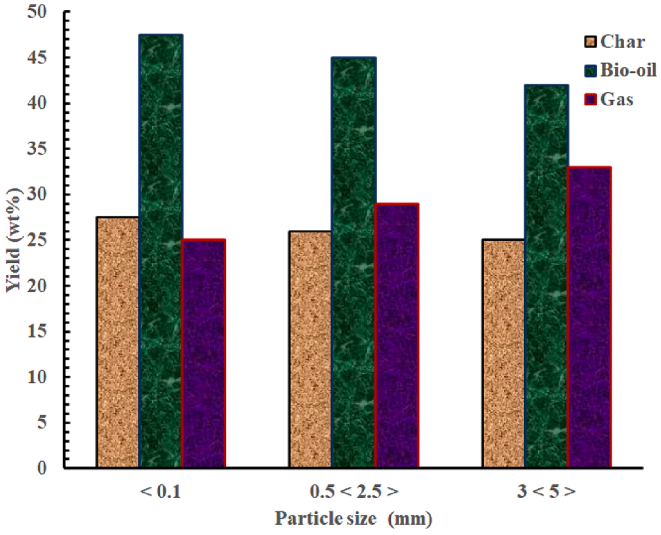


Fig. 4. Particle size influence on the gas, char, and bio-oil, yield.

Detector). (HP-5MS Capillary; 30.0 m × 0.25 mm ID × 0.25 μm film) capillary column was employed and helium gas of 1 μl injection was the carrier gas at a pressure of 7.6 psi. After injecting the sample, the column

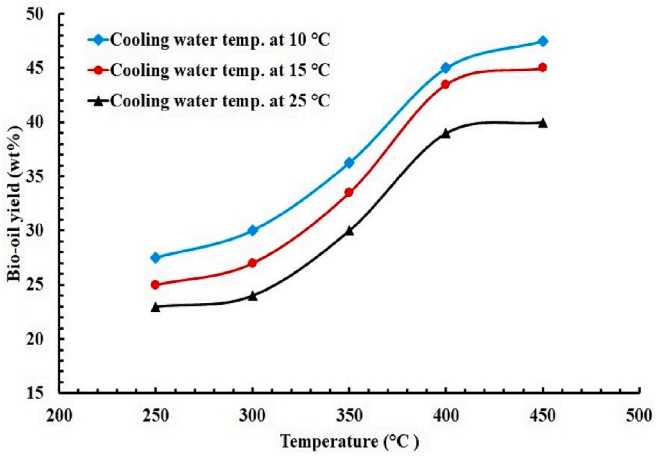


Fig. 5. Cooling water flow rate influence on the gas, char, and bio-oil, char yield.

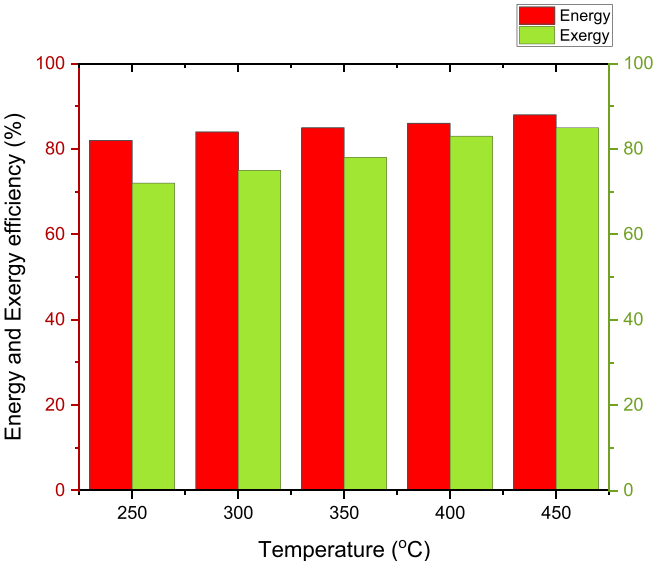


Fig. 6. Energy and exergy efficiency of sawdust pyrolysis at various temperatures.

was held at 60 °C for three minutes before being heated to 300 °C with a 20 °C/min heating ramp and held for five minutes. The injection was carried out in split-less mode at 300 °C. The MS scan range (m/z) was 50–550 atomic mass units (AMU) with electron impact (EI) ionization (70 eV) and a solvent delay of 4.0 min. Mass fragmentations were used to determine the constituents using The NIST mass spectral search tool for the 9NIST/EPA/NIH mass spectral library Version 2.2.

5. Result and discussion

5.1. Biomass characteristics

Table 1 displays the different characteristics of wood sawdust and its biochar. The term "proximate composition" refers to the fixed carbon (FC) content, sample moisture (M), volatile matter (VM), and ash (A). Also, it provides data on a substance's heating and burning capabilities. The sawdust moisture content was (6.70 %) which refers to lower moisture content. This agrees with a previous study that stated that the biomass moisture content in the pyrolysis method should be underneath 10 % [49]. In contrast, sawdust shows a significant volatile content of 73.4 %. Because higher volatile composition biomass specimens are

Table 2
Mass balance, energy, and exergy analysis for pyrolysis of wood sawdust.

Mass balance						
Temperature (°C)	Inputs (kg)	Outputs (kg)				MBC* ratio
	Biomass	Biochar	Bio-oil	Gas	Total	
250	1.0	0.59	0.27	0.10	0.96	0.96
300	1.0	0.56	0.30	0.11	0.97	0.97
350	1.0	0.50	0.36	0.12	0.98	0.98
400	1.0	0.39	0.45	0.14	0.98	0.98
450	1.0	0.34	0.48	0.16	0.98	0.98

Energy balance								
Temperature (°C)	Inputs (kJ)			Outputs (kJ)				EBC* ratio
	Biomass	Process heat	Total	Biochar	Bio-oil	Gas	Total	
250	1818.9	381.82	2200.72	1291.033	373.06	140.5	1804.59	0.82
300	1818.9	409.75	2228.65	1181.93	452.08	238.052	1872.07	0.84
350	1818.9	439.73	2285.63	945.01	629.06	368.72	1942.78	0.85
400	1818.9	484.71	2303.61	878.22	717.164	431.8	2027.18	0.88
450	1818.9	519.69	2338.59	832.58	766.12	482.64	2081.35	0.89

Exergy analysis							
Temperature (°C)	Inputs (kJ)			Outputs (kJ)			
	Biomass	Pyrolysis	Total	Biochar	Bio-oil	Gas	Total
250	2365.55	188.21	2553.76	1346.28	389.18	66.95	1802.4
300	2365.55	188.47	2554.02	1240	499.47	143.46	1882.94
350	2365.55	243.82	2609.37	1115.7	712.7	414.10	2242.5
400	2365.55	286.21	2651.76	961.8	810.9	526.78	2299.51
450	2365.55	325.33	2690.88	909.1	802.55	774.67	2486.31

Table 3
Assessment of sustainability for sawdust pyrolysis.

Temperature (oC)	MBC	EBC	Ψ (%)	SI	IP	$\eta_{wasted\ energy}$	f_{env}
250	0.96	0.82	70.51	3.66	161613.65	0.32	0.42
300	0.97	0.84	73.44	3.84	168259.26	0.32	0.44
350	0.98	0.85	85.61	6.39	131775.52	0.22	0.25
400	0.98	0.88	86.29	6.04	140365.03	0.23	0.27
450	0.98	0.89	91.8	8.33	111727.2	0.17	0.19

more reactive and easily de-volatilized, they are preferred for the pyrolysis process [50]. The inorganic deposit left over after combustion was represented by the ash content in biomass, which would be minimal for the pyrolysis process. Sawdust ash residue was 5.2 % which is lower than 6, and 8 wt% for barley straw, and coal, respectively [51]. Moreover, sawdust has a fixed carbon content of 14.70 %, and the proportion of C and O is greater than the amount of H and N. Through pyrolysis, higher O concentration in biomass creates oxygenated liquid products. However, because WSD has a low nitrogen and sulfur composition, it emits less NO_x and SO_x during the thermochemical conversion procedure. Sawdust's empirical formula, derived from its composition is $CH_{1.83}O_{0.75}N_{0.009}$. The smaller the ratio of H/C and O/C, the bigger the energy content of the substance [51]. As a result, it appears that the current sawdust is adequate for pyrolysis. Sawdust contents of extractive components, lignin, cellulose, and hemicellulose are (20-25%), (45-50%), and (20-25%) respectively.

5.2. Operating parameters influences on the yield of the product

To assess the planned reactor's efficiency, the influence of experimental variables (pyrolysis temperature, cooling water flow rate, and biomass particle size) on the output production of the pyrolysis process was investigated.

5.2.1. Pyrolysis temperature influence on the yield of the products

One of the most critical parameters influencing pyrolysis outputs is the heating rate [52]. Fig. 3 illustrates the impact of pyrolysis temperature on the yield of the pyrolysis products (char, bio-oil, and gas). Increasing the heating temperature in the reactor led to a remarkable reduction in char production. On the contrary, there is a significant increase in the production of gas and bio-oil with the higher heating temperature. The supreme char yield reached 60 wt% at a temperature of 250 °C before it decreased to 35 wt% at 450 °C. However, bio-oil and gas yield rose from 27 and 12 wt% to 55 and 18 wt%, respectively at 450 °C. This trend can be attributed to the decrease in char yields as the temperature increases, while volatile substance yields increase due to primary thermal decomposition and secondary interactions of char with volatiles. [53].

5.2.2. Influence of particle size on the yield of the product

Particle size is another main factor in the pyrolysis process. Three particle sizes were utilized (<0.1, 0.5 < 2.5, >3) mm as shown in Fig. 4. The particle size has a significant influence on pyrolysis; larger particles are related to increased liquid and gas outputs, which is consistent with a previous study [54]. By increasing the particle size, char yield slightly decreased from 27 wt% to 25 wt%. Also, bio-oil yield was reduced from 47 wt% to 42 wt% by increasing the particle size. In contrast, gas yield increased from 24 to 32 wt%. This trend can be attributed to the higher heat transfer efficiency for larger particles, resulting in greater sample decomposition and fewer remaining char residues [55].

5.2.3. Influence of cooling water temperature on the yield of the bio-oil

Fig. 5 shows the effect of cooling water on the bio-oil yield. Three different cooling water temperatures (10°C, 15°C, and 25°C) were utilized in the bio-oil output. It was observed that reducing the cooling water temperature from 25°C to 10°C, at a reactor heating temperature

Table 4
GC–MS analysis of bio-oil at 450 °C.

SI. No.	Retention Time	Peak Area (%)	Compound Name	Molecular Formula
1	4.2703	1.8389	Furan, 2,5-dimethyl-	C_6H_8O
2	4.3447	4.542	Furfural	$C_5H_4O_2$
3	4.831	3.5015	2,4-Dimethylfuran	C6H8O
4	5.1286	5.7758	1,3-Dimethyl-1-cyclohexene	C8H14
5	5.4376	2.8733	Lethane	$C_9H_{17}NO_2S$
6	5.7809	6.5401	2,4-Dimethylfuran	C6H8OC6H8O
7	6.0155	1.8619	2-Furancarboxaldehyde, 5-methyl-	$C_6H_6O_2$
8	6.4275	18.5355	3-Methylpyridazine	C_6H_7N
9	6.8738	13.5453	Mequinol	$C_7H_8O_2$
10	22.5153	7.3923	Phenol, 2-methyl-	C_7H_8O
11	8.4473	4.6439	Phenol, 3,5-dimethyl-	C8H10OC8H10O
12	9.0824	1.2284	2(3H)-Naphthalenone, 4,4a,5,6,7,8-hexahydro-	C10H14O
13	9.1854	2.2666	4-Nitro-3-picoline-N-oxide	$C_6H_6N_2O_3$
14	9.7691	1.8571	2-Butynedioic acid, di-2-propenyl ester	C10H10O4
15	10.3813	3.5934	Phenol, 4-ethyl-2-methoxy-	C9H12O2
16	11.789	0.5777	2-Methyl-Z,Z-3,13-octadecadienol	C19H36O
17	12.2753	0.2649	Citronellal	$C_{10}H_{18}O$
18	13.1737	0.7321	Cyclohexane, 1-(1,5-dimethylhexyl)-4-(4-methylpentyl)-	$C_{20}H_{40}$
19	15.0562	0.9006	6-Octadecenoic acid, (Z)-	$C_{18}H_{34}O_2$
20	15.5254	1.8435	1-methyl-4-phenyl-5-thioxo-1,2,4-triazolidin-3-one	C9H9N3OS
21	16.2406	2.5677	Thymol, TBDMS derivative	C16H28OSi
22	16.4523	0.2741	Ethyl 5-(furan-2-yl)-1,2-oxazole-3-carboxylate	C10H9NO4

of 450°C, led to an increase in production yield from 37% to 45%. This represents a roughly 18% increase in bio-oil yield. This trend is likely attributable to the enhanced heat transfer rate, which increases the rate of condensation, thereby converting more vapor into oil.[56].

5.3. Characteristics of bio-oil and bio-char

To identify the forms of chemical functional groups, an FTIR analysis was utilized. The obtained spectra of bio-oil and bio-char resulting from the pyrolysis of sawdust wastes are depicted for three particle sizes (<0.1 mm, <2 mm, and <5 mm). The spectra were monitored in the transmission mode between 4000 cm^{-1} and 400 cm^{-1} for all samples. For bio-oil, as illustrated in Fig. 6(a), the absorbed light wavelengths indicate that the features of the chemical bonds in the different particle sizes of sawdust bio-oils were similar Strong absorption bands were observed for all bio-oil between 3200 and 3400 cm^{-1} which would be related to the O-H stretching bond indicating the existence of alcohols and phenols. Also, absorption band of 1650 cm^{-1} is related to the stretching C = O bond indicated the presence of aldehydes and ketones. Some weak peaks were observed in absorption bands of 970 to 1350 cm^{-1} which may be associated with the C-O stretching bonds of phenols and alcohols. These results were consistent with Abnisa et al. [57].

For bio-char, as shown in Fig. 6 (b) the presence of a C = C stretching bond at 1645 cm^{-1} denotes the existence of the olefinic compounds. Also, the peaks near 1450, 1110, 840, and 760 cm-1 denote the presence of ketonic, alkyne, aliphatic, aromatic, esters, phenolic, and paraffinic compounds. Hence, pyrolysis was employed to remove as much oxygen as possible, resulting in biochar with a higher heating value and the ability to be utilized as a biofuel [58].

5.4. Mass balance

For investigating the pyrolysis of wood sawdust, a mass balance was conducted. Table 2 presents the mass balance of sawdust at different pyrolysis temperatures. Inputs to the system included the inert gas supply and the mass of wood sawdust, while outputs comprised biochar, bio-oil, and pyrolysis gas. Mass balance coefficients (MBC) ranged from 0.96 to 0.98 at various pyrolysis temperatures, serving to monitor losses. These losses may have arisen from handling procedures and measurement errors [59].

5.5. Energy and exergy analysis

Table 2 illustrates the energy balance of the saw dust pyrolysis system at different temperatures. The inputs included the heat of the pyrolysis reaction and the biomass, while the outputs comprised gas, biochar, and bio-oil. As the pyrolysis temperature increased from 250 to 450 °C, the required heat to achieve the target temperature increased from 381.82 to 519.69 kJ. For the outputs, the energy content of biochar decreased with increasing temperature from 1352.42 to 869.47 kJ. However, the energy content of gas and bio-oil increased with temperature from 167.97 to 494.7 kJ and 301.9 to 749.54 kJ, respectively. Additionally, higher temperatures resulted in improved heating values and mass yields of gas and bio-oil, leading to increased harvested energy and energy balance closures (EBC) ranging from 0.82 to 0.89 for various temperatures. The energy ratio of output to input, represented as EBC, is presented in Table 2. An estimated 11–18 % reduction in energy was observed, which could be attributed to uncertainties in measurement devices, bio-oil condensation on condenser walls, unrecoverable gases, gas chromatograph-detected gas composition, and heat losses, consistent with previous studies [60-62]. The energy evaluation suggests that producing biochar at 450 °C enhances energy efficiency and reduces losses, advocating for scaling up sawdust pyrolysis at high temperatures.

Table 2 also shows the exergy values of yields obtained from wood sawdust pyrolysis. As the pyrolysis temperature increased from 250 to 450 °C, the exergy values of liquid oils ranged from 242.57 to 980.89 kJ / kg_{oil}. This increase may be attributed to the rise in the H/C ratio. Gases exhibited exergy values between 86.27 and 606.84 kJ / kg_{oil}, while biochar exergy ranged from 1491.56 kJ / $kg_{biochar}$. The increase in heating values of oil, and char with temperature rise from 250 to 450 °C was observed, along with a decrease in heat loss due to heat accumulation in the reactor, leading to enhanced energy and energy efficiency [63,64].

5.6. Energy and exergy efficiency

The pyrolysis process demonstrated a synchronized trend of exergy and energy efficiency, significantly influenced by the pyrolysis temperature, as shown in Fig. 6. Energy efficiency was observed to surpass exergy efficiency. Based on the resulting yields, heating value, and pyrolysis temperature, energy and exergy efficiency ranged from 82 % to 88 % and 72 % to 85 %, respectively. The temperature played a crucial role in the thermodynamic analysis of the pyrolysis process. Higher temperatures led to thermal cracking of char, transforming solid and liquid phases into gaseous states. Additionally, lower heat loss was observed at higher temperatures due to the accumulation of heat in the reactor, resulting in enhanced energy and exergy efficiency.

5.7. Sustainability analysis

The assessment of energy utilization within the ecosystem can contribute to mitigating adverse environmental effects. A green building analysis was conducted on pyrolysis technology using metrics such as improvement potential (IP), environmental impact factor (f_{env}), and sustainability index (SI). The environmental impact of the pyrolysis process was evaluated based on IP and SI, lost energy, and f_{env}. The

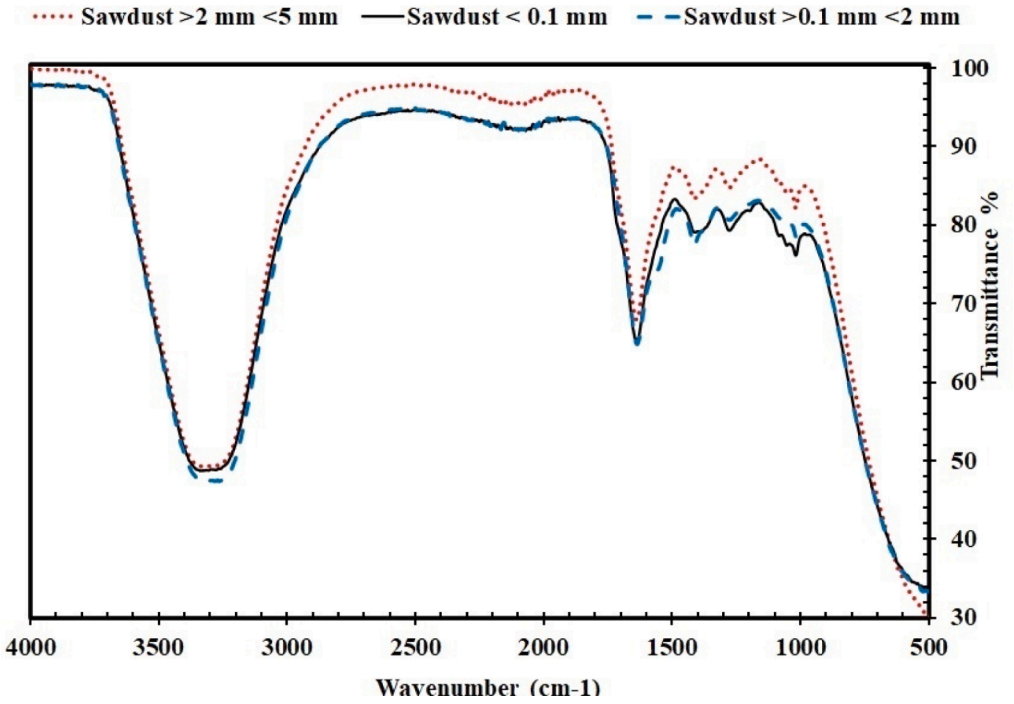


Fig. 7. FTIR spectra of WSD (a) bio-oil and (b) bio-char.

indicator of energy waste reflected a negative environmental impact, which decreased with the increased exergy efficiency and reduced system losses of the process. As the pyrolysis temperature increased, SI increased from 3.66 to 8.33, indicating a lesser impact on the environment. The ratios of waste energy and environmental factors decreased from 0.32 to 0.17 and 0.42 to 0.19, respectively. Additionally, it was noted that low-temperature pyrolysis systems exhibited a higher upside potential compared to elevated ones, as illustrated in Table 3.

5.8. Chemical properties of bio-oil

The resulting bio-oil was analyzed using GC–MS to identify the types of chemical compounds present. Fig. S1 depicts the GC–MS curve for temperature increments of 250, 300, 350, 400, and 450 °C. Tables 1, 2, 3, and 4 present the identification of pyrolysis bio-oil compounds at 250, 300, 350, and 400 °C, respectively. Table 3 illustrates the GC–MS compounds of bio-oil at 450 °C. Although bio-oil comprises various

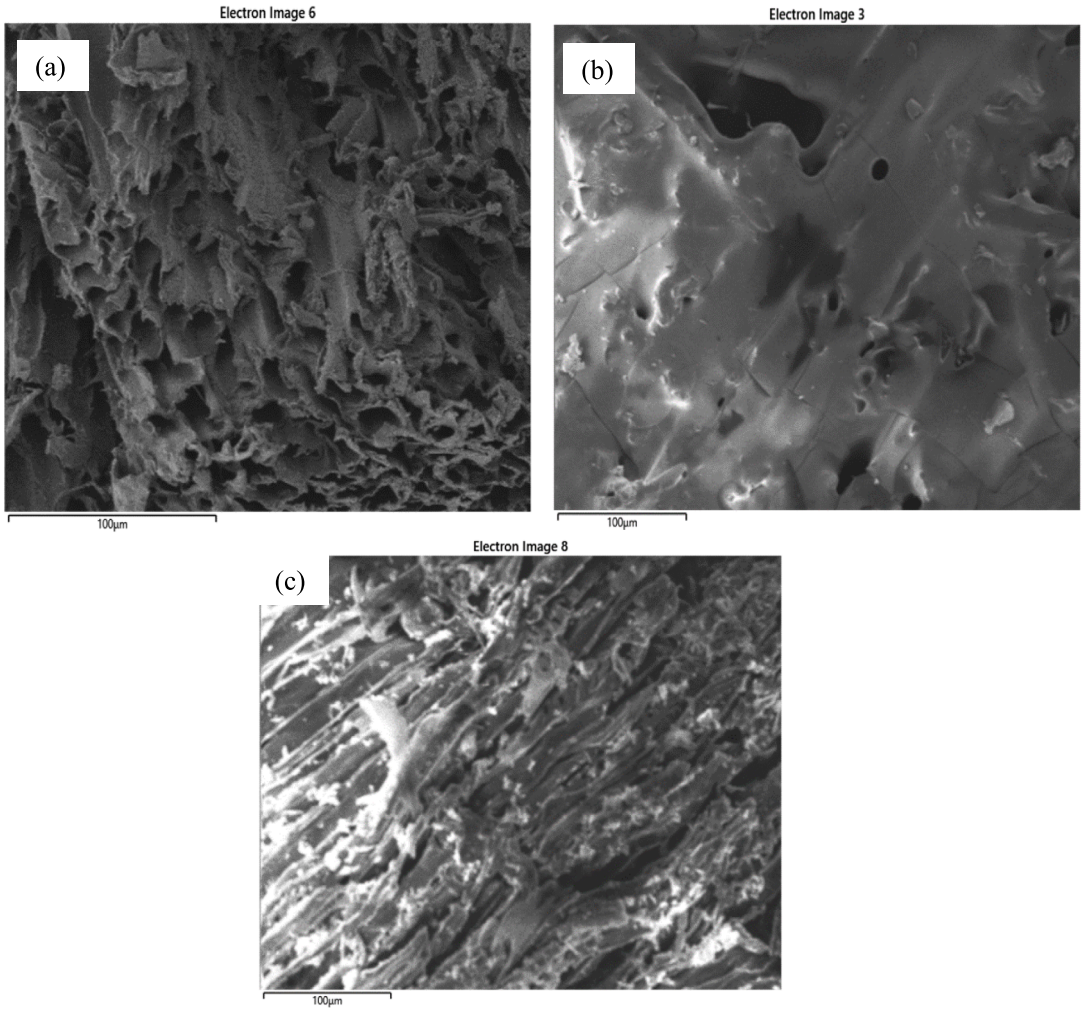


Fig. 8. FESEM image of biochar at particle size (a) < 0.1 mm, (b) (0.5 – 2) mm, and (c) (2.5 – 5) mm, all samples are at 450 °C.

chemical compounds, 3-methylpyridazine, Mequinol, phenol, and their derivatives exhibited the highest peak areas among the identified substances. While bio-oil contains a wide array of chemicals, those with low peak areas were not included in this study. The majority of compounds listed in Table 3 are fully oxygenated, resulting in a minor heating value due to the high oxygen content in bio-oil, consistent with findings from previous studies [65,66].

5.9. Pyrolytic gas composition

The gas production composition of sawdust waste pyrolysis at various heating temperatures is illustrated in Table 4. The outcomes revealed that CO, CO_2, CH_4, and H_2 were the major gas elements during the process. By increasing the heating temperature from 250 to 450 °C, the H_2/CO ratio increases from 0.638 to 0.746. Moreover, CO_2 and CO were the major gases at lower temperatures. i.e. The release of CO_2 and CO happens due to the degradation of cellulose [67].

5.10. SEM and EDX analysis of bio-char

Fig. 7 displays the FESEM image of biochar from different particle sizes < 0.1, (2.5–5), and (0.5–2) mm. All samples are at 450 °C. As shown, the numerous pores and fissures on the exterior of bio-char, indicate the elimination of change in volume from biomass through pyrolysis [22]. Also, the surface morphology was shown to be less rough by increasing the particle size. This trend may be owing to the resulting liquids and gas yields increased due to larger particles [68].

EDX spectra of bio-char for three different sizes are shown in Fig. 8. The EDX investigation of sawdust indicated that it generally consists of O and C in high concentration as shown in Fig. 8 (a). However as displayed in Fig. 8 (b), and (c) by increasing the particle size the presence of Fe, Zn, Mg, and Ca were detected. Such inorganic (Fig. 9) substances consist of the ash content of the biochar [67].

Conclusion

The furniture industry is one of the most important and necessary industries in all countries. The wood residues from this industry are misused and disposed of. One of the most promising ways to exploit this waste is to pyrolyze it to produce biofuels. To evaluate the efficiency of the wood sawdust pyrolysis procedure, thermodynamic analysis, the effect of operating temperature on production yield, mass balance, energy and exergy, and environmental sustainability were evaluated. The experimental analysis of WSD for extractive components, lignin, cellulose, and hemicellulose were 2.15, 11.23, 47.62, and 39 %, respectively. The present work is driven by a pyrolysis reactor at a temperature of 450 °C and a heating rate of 10 °C/min. The results revealed that for WSD particle size of < 1 mm, the maximum yield for bio-oil and biochar were (47 wt%), and (27 wt%), respectively. The production of bio-oil first boosts with increasing temperature reaches an optimum at an

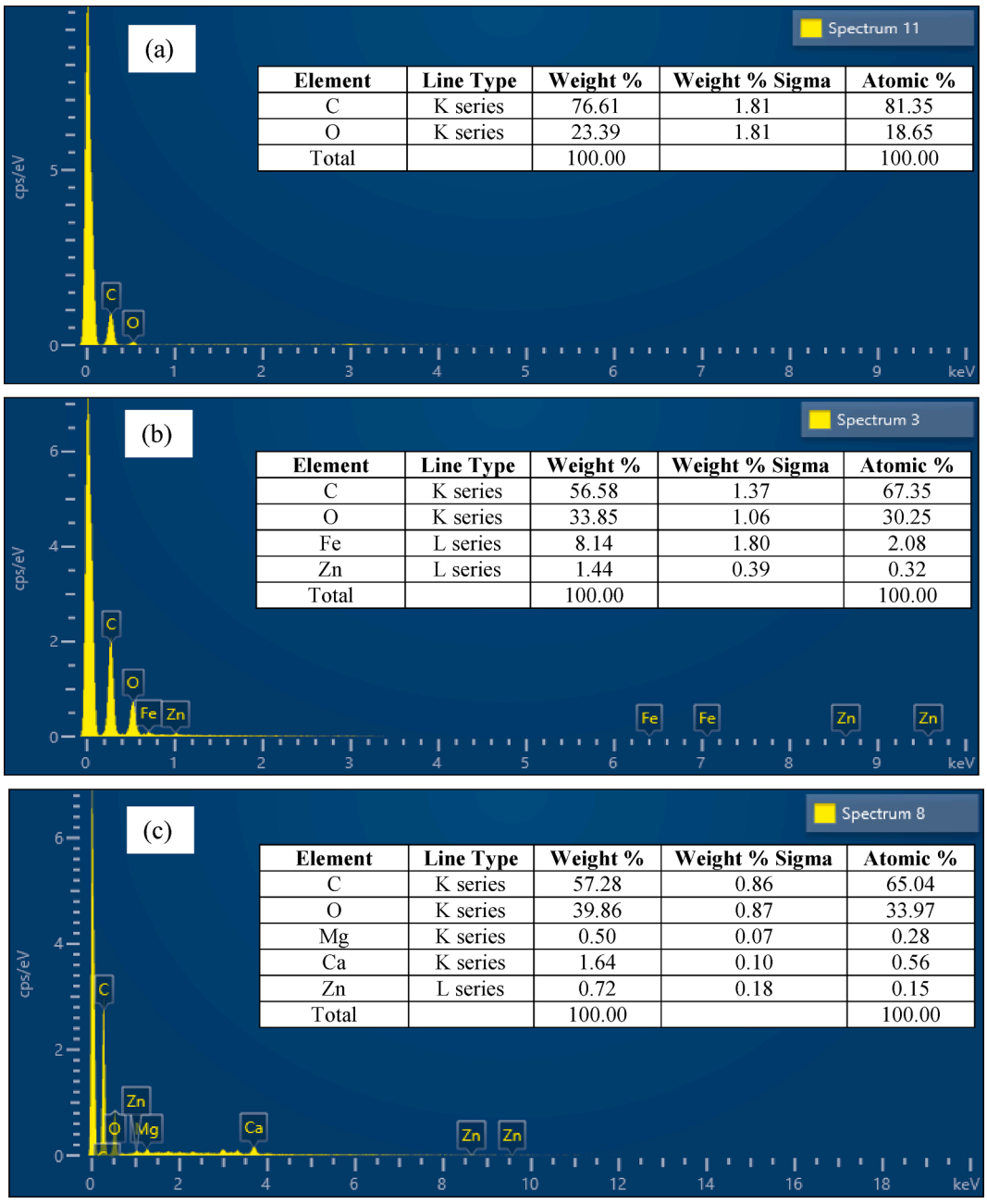


Fig. 9. EDX spectra of biochar particle size (a) < 0.1 mm, (b) (0.5 – 2) mm, and (c) (2.5 – 5) mm, all samples are at 450 °C.

Table 5
H_2 to CO ratio and specific energy of the pyrolysis gases at different temperatures.

Heating temperature (°C)	Specific energy consumption (kJ/kg)				H_2/CO
	(CO_2)	(CO)	(CH_4)	(H_2)	
250	15.50	46.77	7.88	29.85	0.638
300	13.20	46.98	6.89	32.93	0.70
350	13.00	47.12	6.01	33.87	0.72
400	12.33	47.40	5.75	34.52	0.728
450	12.01	47.52	5.03	35.44	0.746

approximate temperature of 450 °C and then drops. The yield of gaseous products rises, whereas the yield of biochar decreases continually with expanding temperature. At various pyrolysis heating temperatures. The mass balance closure (MBC) was investigated to be between 0.96 and 0.98. By increasing the pyrolysis heating temperature from 250 to 450 °C, the exergy and energy efficiencies have increased from 72 % to 85 % and 82 % to 88 %, respectively. After doing a sustainability evaluation, it was discovered that at 450 °C process temperature, there was a smaller environmental impact factor (0.17) and a higher sustainability index (8.33). In the pyrolytic gas stream outflow, there was a good percentage of H_2, CH_4, CO, and CO_2. Reducing the cooling water temperature from 25 to 10 °C can boost the production yield of bio-oil from 37 % to 45 %.

CRediT authorship contribution statement

Yasser Elhenawy: Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kareem Fouad:** Investigation, Formal analysis, Conceptualization. **M. Bassyouni:** Validation, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **O.A. Al-Qabandi:** Validation,

Software, Methodology, Investigation, Formal analysis, Conceptualization. **Thokozani Majozi:** Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecmx.2024.100583.

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