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Pyrolysis of Agricultural Biomass using an Auger Reactor: A Parametric Optimization

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Abstract: A 500 L biomass fast pyrolysis Auger reactor was designed, constructed and experimented with biomass of Mesquite (*Prosopsis juliflora*) and rice straw (*Oryza sativa*). The thermogravimetric analysis of feed stock and the physico chemical properties of the feed and product bio-crude was done as per ASTM standard. An optimization based on Response Surface Methodology was carried out for the operating parameters chosen as: (1) reactor temperature, (2) feedstock-heat carrier ratio and (3) rotational speed of the auger reactor. The optimum bio-crude yield of 42.6 wt.% was observed at 500 °C, feedstock-heat carrier ratio 1:2 and 30 rpm for mesquite sawdust and 34.6 wt.% at 475 °C, 1:2 ratio and 50 rpm for rice straw. Among the two kinds of feedstock tested, the sawdust yielded better product under identical operating conditions. The final bio-crude have properties similar to the results that was reported in the past and has HHV-higher heating value less than petroleum fuel.

Keywords: bio-energy, pyrolysis, auger reactor, mesquite sawdust, rice straw, optimization

1 Introduction

The world we live in has been using fossil based fuel sources for power since centuries. This may have been a smart choice at the time but, tides are now shifting towards sustainability. To reduce consumption of non-renewable resources, the use of renewable ones should increase. The replacement of fossil fuel by biomass is a promising option for power technologies as well as for synthetic fuel production (Piekarczyk et al. 2013). Biomass can be transformed to energy by a number of routes including biochemical, thermal and mechanical procedures. Biochemical methods include fermentation where the use of microbes helps conversion of biomass into useable products. While organic processing results in a slight number of distinct products in high yield, thermal conversion provides multiple products in shorter time (Bridgwater 2012; Himmel et al. 2007; Houghton, Weatherwax, and Ferrell 2006). Thermochemical processes are driven by the application of heat causing morphological and physicochemical changes in the biomass. Pyrolysis has been used for many years in production of charcoal but, it is only in the last 35 years that pyrolysis of biomass at temperatures (~500 °C) (Salehi et al. 2013) and short residence times (~2s) has become of significant interest (Pilon and Lavoie 2013). The process of pyrolysis produces an organic phase, a solid residue and a gaseous mixture. In this study, the organic phase will be called as bio-crude, the solid residue biochar and the gas mixture will be referred to as non-condensable gases. Pyrolysis produces liquid products of up to 55 wt.% which can be employed directly as effective energy carriers (Cordella et al. 2013). Fast pyrolysis process requires approximately 15 % of the feedstock energy for providing the heat for the endothermic process (Kohl, Laukkanen, and Järvinen 2014). Auger technology is adapted from the Lurgi process for coal gasification (Francis and Peters 1980). Use of simple peripheral heating devices in the auger reactor, leads to possible disproportionate heat transfer through the volume, this will in turn cause a non-homogeneous product array. A heat carrier ensures complete and uniform transfer of heat to the biomass while, the auger works as a mixer. This design gives good control over the biomass residence time and does not dilute the pyrolysis products with a carrier gas (Fernandez-Akarregi et al. 2013).

Mesquite (*Prosopis juliflora*) is a common desert plant with edible beans. In American Indian history, it has been used to treat ailments like diarrhea, sore throat, soothe ailing eyes, heal flesh wounds and headache (Felger and Moser 1971). Rice (*Oryzum sativa*) stalk is one of most abundant biomass material whose production totals around 129 mega tonnes per annum in India (Gadde, Menke, and Wassmann 2009). Currently exhaustive attention has been paid towards agricultutral wastes,

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much like rice stalk as a renewable energy source (Moliner et al. 2016; Restrepo and Bazzo 2016; Wu et al. 2016). Conversion of rice stalk and mesquite using pyrolysis has not been studied intensively and most reported works (Balagurumurthy et al. 2015; Chen et al. 2015) are confined to a laboratory scale units. Many works have been reported on pyrolysis of biomass to produce biocrude like: switchgrass (Yang et al. 2014), babul plant saw dust(Kothari, Shah, and Murugavelh 2015), pine sawdust (Mamaeva et al. 2016), cellulosic biomass (Zheng et al. 2016), torrefied bamboo (Mi et al. 2016), waste tea (Tian et al. 2016) and nordic grassland wastes (Johansson et al. 2016). All these works have successfully proven the use of pyrolysis in both lab and pilot scales. A lower temperature operation with extended vapour residence time favors charcoal formation while higher temperatures intensify conversion to gas. An optimum operation at moderate temperatures and small vapour residence time are most favourable to production of liquid products.

This work aims at an optimization of the operating conditions for production of biocrude from mesquite sawdust and rice stalk in an auger pyrolysis reactor. This is achieved by a response surface methodology (RSM) driven operation. The reactor is one of the first of its capacity reported in India. Also, there is no large-scale commercial implementation of the auger technology in biocrude production, hence this work will serve as the basis of future endeavors.

2 Materials and methodology

2.1 Feedstock preparation

Mesquite sawdust was collected from a sawmill in Vellore, India. The saw dust was further milled and samples of 2 mm were chosen for pyrolysis. Rice straw collected from paddy fields in Kancheepuram, Tamil Nadu were chopped to preset 2 mm length, washed and dried. The samples were dried using a solar dryer based on method published earlier (Subahana et al. 2006; Subahana and Natarajan 2016). Dried samples were stored in dehumidified chambers at 4 °C till it fed to the reactor.

2.2 Feed characterization

Moisture Content (MC), volatile combustible matter (VCM) and ash were determined by ASTM D3173, ASTM E3175 and ASTM E1755 respectively. Carbonaceous component was obtained by substracting the sum of ash, mixture and volatile matter. Ultimate analysis of C, H, N, O and S was done using a Elementar Vario EL III elemental analyzer. Heating value was determined using the 6750 Semimicro Calorimeter. Thermal stability of both feedstock was evaluated by TAQ 500 thermo gravimetric analyzer (TGA) operated using N_2 as purge.

2.3 Pyrolysis

Pyrolysis was carried out in a 500 L single shaft auger reactor as shown in Figure 1, from the biomass power plant located in VIT University, Vellore, India. The reactor was built with a radius of 0.3 m and a heating length of 1.2 m. The auger was running using a variable speed motor and the feedstock were feed into the system using a hopper. The reactor was purged with nitrogen prior to runs. Sand was preheated to reaction temperature and mixed with biomass in predetermined ratio (1:1, 2:1 or 3:1) in the heated reactor. Pyrolysis was conducted at three temperatures; 475, 500 and 525 °C and three auger speeds; 10, 30 and 50 rpm. The reactor was run in continous mode at 10 kg/h for 3 h for one set condition. The oil was condensed by a 3 staged chiller and was collected for further analysis. Syngas was measured by water displacement and bio-char was collected for mass balance and further analysis. Few experiments were performed repeatedly to validate the consistent of the data.

2.4 Product characterization

The moisture content in the biocrude was determined using ASTM E203 (Karl-Fischer Titration). GC/MS of biocrude analysis was performed on a Perkin-Elmer Clarus 680 (GC) equipped with an Clarus 600 mass selective detector (MSD). Helium at a flowrate of 1 mL/min was employed as the carrier gas. An Elite-5MS column (30 m, 0.25 mm ID, 250 μm df) was utilized. The injection was set at 250 °C with a split ratio of 10:1 and injection volume of 1 μL. The column temperature was programmed to range between 60 °C (hold for 2 min) and 300 °C (hold for 6 min) at a heating rate of 10 °C/min. The MS conditions were set at solvent delay of 2 min, transfer temperature 230 °C, source temperature 230 °C and scan 50–600 Da. The biocrude samples were prepared as 10 wt.% solution in methanol. Proximate and ultimate analyses and heating value of biocrude were determined using protocol above under feedstock characterization. Bio-char from different

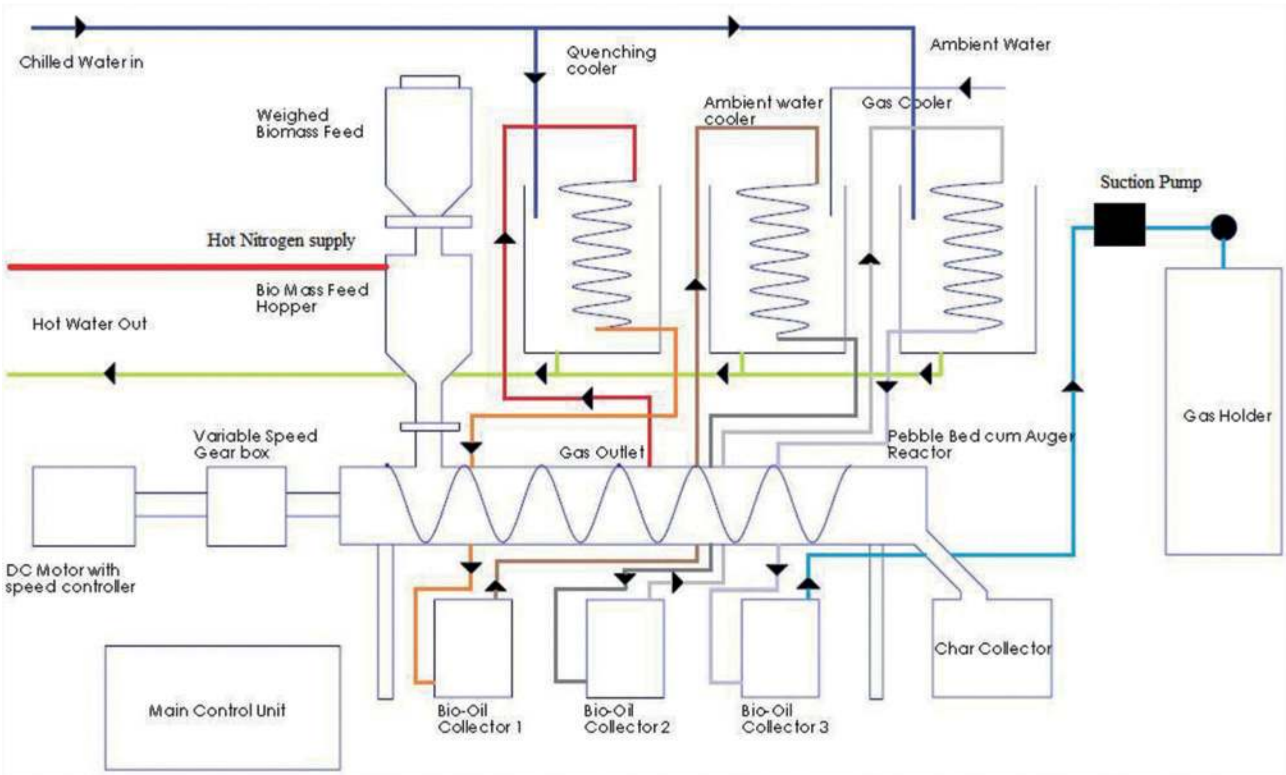

Figure 1: **S**chematic diagram of 500 L Auger reactor.

conditions was tested for heating value, proximate and ultimate analyses using protocols as discussed.

2.5 Choice of process variables and conditions

Process variables and respective ranges in the pyrolysis study were based on preliminary experimentation, single-factor experiments and previously published works:

a) A wide range of heat carriers (sand, semi-coke, boiler and shale ash, limestone, nitrogen and helium gases) were examined initially. Design constraints and observed non uniformities in heat transfer led to only dry sand being chosen as the heat carrier. Further, earlier works advocate use of dry sand due to its large heat capacity and high heat rate (Guoxin et al. 2008; Ma et al. 2014).

b) To optimize heat transfer, the ratio of sand and biomass was varied between 1:1, 2:1, 3:1, 4:1 and 5:1 during preliminary testing. It was observed that any increase of the ratio above 3:1 yielded no significant increase in yields. Similar results have been reported (Guoxin et al. 2008; Ma et al. 2014; Veses et al. 2016).

c) The thermochemical conversion processes of biomass takes place between 180 °C and 1,500 °C (Veses et al. 2016). This study uses 475, 500 and 525 °C as the reactor temperatures, mostly the pyrolysis is executed between 350 and 700 °C (Goyal, Seal, and Saxena 2008).

d) The optimum vapor residence time for fast pyrolysis is reported to be 1.03 sec (Sulaiman and Abdullah 2011). The study tries to optimize the residence time by control over the auger speed. The speed is varied between 10, 30 and 50 rpm. Below 10 rpm, initial runs showed a residence time above 7 sec and lower bio-crude yields. This may have been due to secondary reactions that occur in longer residence times, causing formation of gases like CO_2 and CO (Chen et al. 2014; Patwardhan et al. 2011).

2.6 Experimental design

Response surface methodology (RSM) was used to achieve an optimum region for the operation of the reactor. The significant advantage of this method is: i) to understand how process variables affect the selected response, ii) to determine existence of any interrelationships and iii) to characterize combined effect of all variables (Pillai et al. 2009). Process optimization was performed by a three factor three stage RSM employing Box-Behnken design. The following independent input variables and factor level were selected: 475 °C, 500 °C and 525 °C for reactor temperature (X_1); 1:1, 2:1 and 3:1 for ratio of heat carrier to biomass feed (X_2) and; the auger rotational speed (X_3) as 10, 30 and 50 rpm (Table 1).

Table 1: List of Box-Behnken Design independent variables chosen for optimization.

Variable	Level		
	−1	0	1
Reactor temperature (°C), $\mathbf{X_1}$	475	500	525
Heat carrier to biomass ratio, $\mathbf{X_2}$	1	2	3
Auger speed (rpm), $\mathbf{X_3}$	10	30	50

To minimize effects of uncontrolled factors in observed yields and human errors, a randomized sequence of 27 experimental runs were performed for each feedstock (Table 2). A second order polynomial equation was obtained using the independent variables as mentioned in eq. (1)

$$Y = A_0 + \Sigma A_1X_1 + \Sigma A_2X_2 + \Sigma A_3X_3 + \Sigma A_{12}X_1X_2 + \Sigma A_{13}X_1X_3 + \Sigma A_{23}X_2X_3 + \Sigma A_4X_1^2 + \Sigma A_5X_2^2 + \Sigma A_6X_3^2 \quad (1)$$

where, Y is the predicted biocrude yield, A_0 the intercept coefficient, A_i the linear terms, A_{ii} the squared terms, A_{ij} the interaction terms and X_i represents the coded independent variables for the model (Table 1). Analysis of variance (ANOVA) was performed to identify interaction between variables and responses. The significance was checked by F-Test value and quality of fit was expressed by coefficient of determination (R^2).

3 Results and discussion

3.1 Feedstock characterization

The dry basis physical and elemental analyses of feedstock used are presented in Table 3 which is as similar reported (Chen et al. 2012; Moliner et al. 2016). From proximate analysis, it was observed that the moisture content, volatile matter, fixed carbon and ash content of sawdust were 15.3 wt.%; 60.4 wt.%; 24.2 wt.% and 0.1 wt.% respectively. These values were 8.30 wt.%; 51.75 wt.%; 28.41 wt.% and 11.54 wt.% for rice straw. Alkali metals contained in ash may act as catalysts for changing depolymerization mechanisms during pyrolysis, resulting in changes in the composition of pyrolysis products (Fahmi et al. 2007). In this study, possible catalytic effects were not considered since as the ash content was below 1 wt.%. The heating value of mesquite sawdust was 5224.42 Btu/lb or 12.152 MJ/kg and 5591.15 Btu/lb or 13.005 MJ/kg for rice stalk. From thermo gravimetric studies (Figure 2), it is observed that the values are in acceptance of those reported in proximate analyses (Table 3).

3.2 Effect of temperature

Bio-crude, bio-char and gas phase product ratios varied with temperature (Figure 3). Generally, with increase of temperature, gas yields increased and bio-char yields decreased. The effect of temperature on bio-crude yields were more dependent on the feedstock used (Tsai, Lee, and Chang 2006). Optimum temperature for pyrolysis of mesquite sawdust was observed to be 500 °C while slightly lower at 475 °C for rice straw. This may be attributed to the physical and chemical composition of both feedstocks. Pyrolysis of sawdust at 500 °C yielded 42.6 wt.% bio-crude and 28.6 wt.% gaseous products as reported by (Nam et al. 2015), whereas pyrolysis of rice straw at 475 °C yielded 34.6 wt.% bio-crude and 32.7 wt.% gas (Figure 3). Pyrolysis products from similar agricultural and herb residue wastes determined at different temperatures by (Azargohar et al. 2014) and (Wang et al. 2010) had trends similar to those observed in this study.

It is expected to have greater bio-crude yields at higher temperatures due to greater heat transfer but above the optimum, a greater chance for secondary reactions is prevalent (Onay 2007; Yang et al. 2007). Increase in gaseous products at higher pyrolysis temperatures for both feedstocks is due to secondary decomposition of vapors and bio-char. Similar trends in gas production was reported in other studies (Horne and Williams 1996; Luo et al. 2004).

3.3 Effect of heat carrier and vapor residence time

The effect of biomass and sand mixture ratios has been studied between 1:0 and 1:3 at all pyrolysis temperatures and speeds. The product yield of both biomasses at

Table 2: List of experiments done for both the feedstock with product distribution.

Expt. No	Temperature (°C)	Biomass – heat carrier Ratio	Rotational Speed (rpm)	Product composition					
				Mesquite sawdust			Rice straw		
				Bio-crude (%)	Biochar (%)	Gas (%)	Bio-crude (%)	Biochar (%)	Gas (%)
1	475	1:1	10	27.3	40.2	32.5	21.7	40.6	37.7
2	475	1:1	30	33.8	45.6	20.6	25.3	37.5	37.2
3	475	1:1	50	18.3	38.4	43.3	28.9	36.5	34.6
4	475	1:2	10	30.1	46.7	23.2	27.8	36.1	36.1
5	475	1:2	30	35.4	49.8	14.8	31.3	35.4	33.3
6	475	1:2	50	28.1	41.2	30.7	34.6	32.7	32.7
7	475	1:3	10	26.8	41.3	31.9	22.8	35.6	41.6
8	475	1:3	30	31	43.2	25.8	27.6	36.2	36.2
9	475	1:3	50	20.8	39.1	40.1	31.8	35.6	32.6
10	500	1:1	10	31.7	32.8	35.5	20.2	39.9	39.9
11	500	1:1	30	38.4	31.2	30.4	24.8	35.6	39.6
12	500	1:1	50	28.4	31.5	40.1	27.4	34.3	38.3
13	500	1:2	10	37.8	31.1	31.1	27.6	32.6	39.8
14	500	1:2	30	42.6	28.8	28.6	29.4	30.2	40.4
15	500	1:2	50	35.7	31.2	33.1	32.4	28.7	38.9
16	500	1:3	10	29.2	32.6	38.2	25.1	30.2	44.7
17	500	1:3	30	35.6	31.5	32.9	27.3	25.6	47.1
18	500	1:3	50	26.4	33.5	40.1	30.9	26.5	42.6
19	525	1:1	10	32.5	28.7	38.8	10.8	22.3	66.9
20	525	1:1	30	36.2	26.5	37.3	16.9	35.1	48
21	525	1:1	50	29.1	29.5	41.4	22.6	38.4	39
22	525	1:2	10	36.9	30.2	32.9	19.3	39.4	41.3
23	525	1:2	30	39.7	31.4	28.9	23.7	38.5	37.8
24	525	1:2	50	31.4	30.8	37.8	28.7	35.1	36.2
25	525	1:3	10	30.2	29.2	40.6	17.3	39.4	43.3
26	525	1:3	30	34.1	33.5	32.4	21.3	38.9	39.8
27	525	1:3	50	24.4	30.5	45.1	25.1	37.6	37.3

Table 3: Physicochemical properties of both feedstock and bio-crudes at optimized conditions.

		Mesquite sawdust		Rice straw	
		Feedstock	Bio-crude	Feedstock	Bio-crude
Moisture content	wt %	15.30	9.20	8.30	8.10
HHV	MJ/kg	12.15	19.52	13.01	13.21
Density	kg/m^3	240.28	1209.78	188.44	1326.05
Volatile matter	wt %	60.40		51.75	
Fixed carbon	wt %	24.20		28.41	
Ash content	wt %	0.10		11.54	
Carbon	wt %	45.95	62.52	47.52	65.21
Hydrogen	wt %	8.77	7.85	6.30	4.46
Nitrogen	wt %	2.12	0.50	0.20	0.10
Oxygen	wt %	43.16	29.13	45.98	30.23
O/C	mol/mol	0.71	0.35	0.73	0.35
H/C	mol/mol	2.28	1.50	1.58	0.82

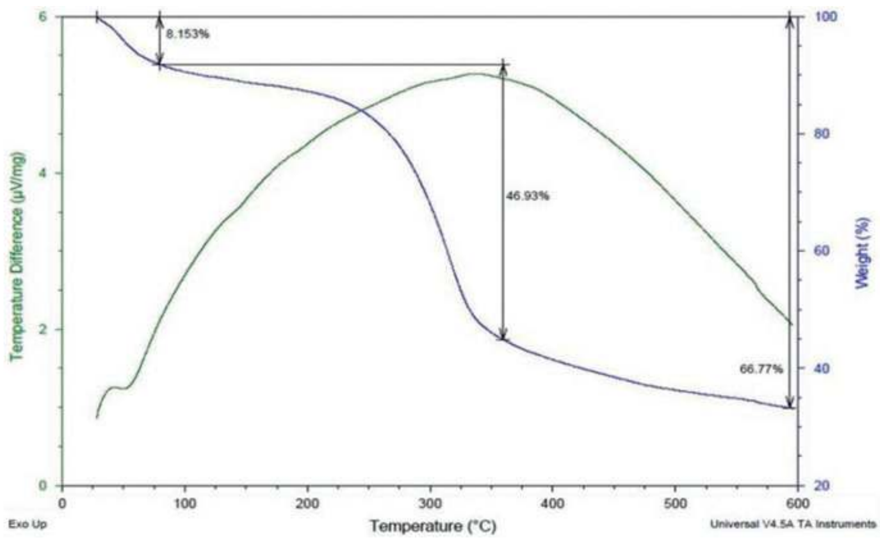

Figure 2: Thermogravimetric curves for rice straw.

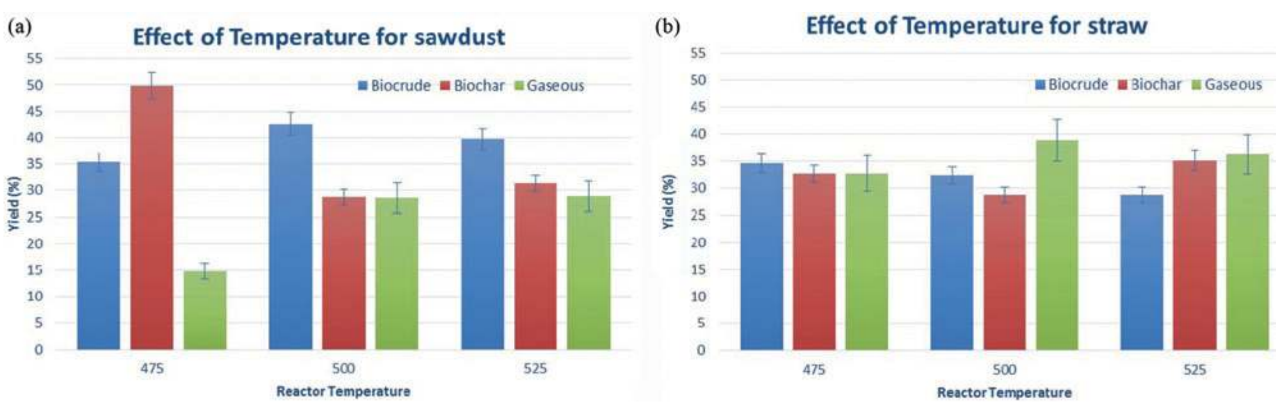

Figure 3: Effect of temperature on yields: (a) mesquite sawdust and (b) rice straw.

optimum temperatures is shown in Figure 4. The production of crude increased from 38.4 % to 42.6 % and from 28.9 % to 34.6 % with increase in heat carrier ratio to 1:2 in both biomasses. This is due to the heat transfer coefficient of solid heat carrier being greater than the coefficient of thermal radiation. The biomass contacts the solid heat carrier directly, and the temperature of biomass is increased in a shorter time due to the heating rate (Brown and Brown 2012; Liaw et al. 2013) Large amount volatile matter was evolved rapidly. In addition, sand particles of small diameters can promote the heat transfer effectively. However, a decrease in production of bio-crude occurs under the condition of excessive solid heat carrier loading. This might be associated with secondary decomposition by escape of volatile oil fraction through the carrier.

The yield resulting from varying the auger speed is represented in Figure 5. Varying speeds, are seen to vary the residence time of vapors within the reactor space. This may be due to the vapor pressure developed from pyrolysis of biomass. The hot vapor residence time is calculated as the time between input of biomass and the observance of the first bio-crude drop. It is apparent from Figure 5, that there is a maximum crude yield and a minimum char yield at an auger speed of 30 rpm for sawdust and 50 rpm for rice straw. This is in agreement with similar results obtained by Brown and Brown (2012) for red oak wood. For higher auger speeds it is likely that biomass is moved out of the reactor before it can fully pyrolyze. While the char collector is at the same temperature as the reactor, any vapors released in there will have extensive contact with char, which is well known and

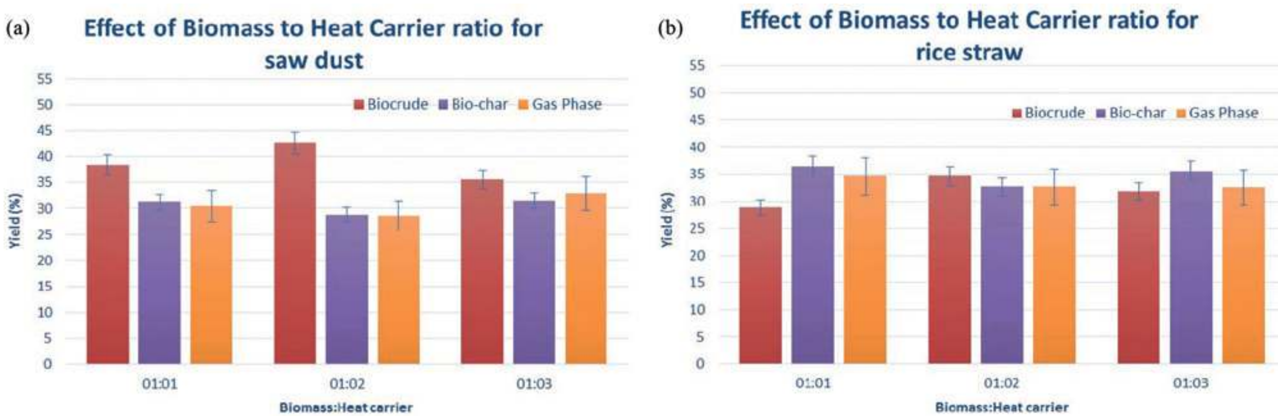

Figure 4: Effect of biomass-heat carrier ratio on yields: (a) mesquite sawdust and (b) rice straw.

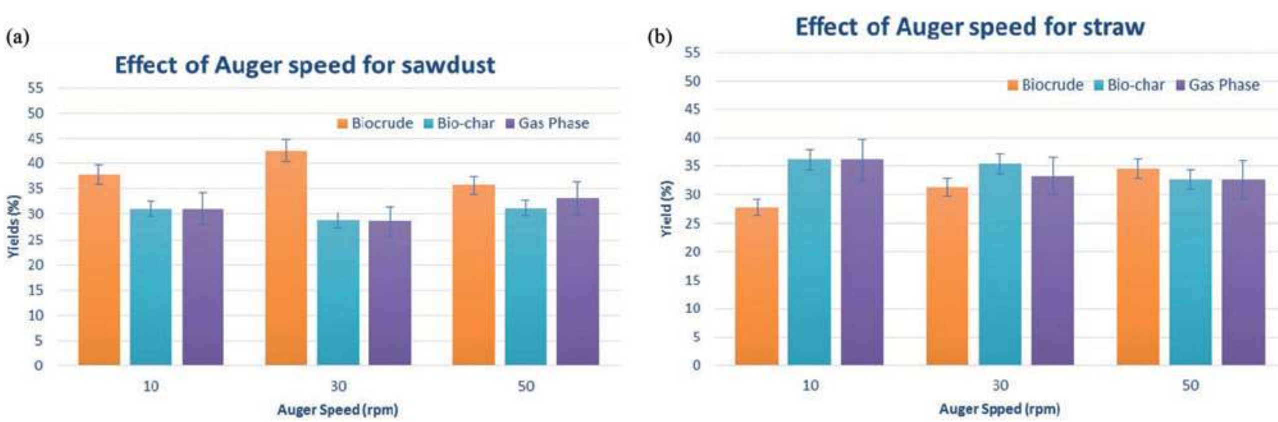

Figure 5: Effect of auger speed on yields: (a) mesquite sawdust and (b) rice straw.

lead to increased char yield. In addition, any tars sticking to the char would contribute to the measured char yield. For longer residence time secondary reactions will result in decomposition of the volatile vapors. This clearly shows the sensitivity of yields to variations in auger speed and there is a need to optimize this variable.

3.4 Optimization of total extraction yield

A three factor-three level Box-Behnken design was used to develop a correlation between the process variables and yield of biocrude. The raw experimental data were fed into the Design Expert 10 software (Stat-Ease, Inc., 2021 East Hennepin Ave., Suite 480, MN, USA) for further analysis. Without performing any transformation on the response, examination of Fit Summary revealed that a quadratic model is statistically significant for all cases within the scope of this study and therefore it was used throughout the investigation. Design of Experiment reduce experimental trials without impairing the precision of results. The set of experiments, generated by the software fixing various levels of operational parameters for both feedstock, were performed (Table 2). The following correlations were generated for the pyrolysis process under study. Bio-crude yields from pyrolysis of mesquite sawdust (eq. (2)) and rice straw (eq. (3)) are shown as:

$$Y = -1311.2500 + 5.1565X_1 + 18.1875X_2 + 1.9644X_3 + 0.0069X_1X_2 - 0.0018X_1X_3 - 0.0025X_2X_3 - 0.0050X_1^2 - 5.6750X_2^2 - 0.0196X_3^2 \quad (2)$$

$$Y = -641.1219 + 2.9035X_1 - 11.6875X_2 - 0.4644X_3 + 0.0569X_1X_2 + 0.0013X_1X_3 - 0.0175X_2X_3 - 0.0032X_1^2 - 3.7125X_2^2 + 0.0005X_3^2 \quad (3)$$

Adequacy check is a prime requirement in the analysis to ensure approximation of the proposed model to real systems (Körbahti and Rauf 2008). It was performed in this study by test of significance of individual and regression model coefficients. The negligible lack of fit values and low P-values indicated that the generated models could be used to predict desired response. The model accuracy and precision were verified by the coefficient of determination ($R_2 > 0.99$). Moreover, predicted R_2 (0.9169 for mesquite sawdust and 0.8962 for rice straw) was in good agreement with the adjusted R2 indicating adequate approximation of the proposed model with actual. In addition, the signal to noise ratio was found to be > 40 indicating goodness of fit. The regression equations (eqs (2) and (3)) were then modified through the test for ANOVA to include only the statistically significant terms based on the P-values (<0.001) (Table 4). The modified equations are as follows: Bio-crude yield from pyrolysis of mesquite sawdust (eq. (4)) and rice straw (eq. (5)) as the feedstock are given below

Table 4: ANOVA table showing p-values and significant variables.

Source	Mesquite sawdust	Rice straw
Model	<0.0005	<0.0005
A-Temperature	<0.0005	<0.0005
B-HC:Biomass	0.0019	0.0043
C-Auger Speed	<0.0005	<0.0005
AB	0.6008	0.0225
AC	0.0289	0.2253
BC	0.8800	0.4972
A^2	<0.0005	0.0039
B^2	<0.0005	<0.0005
C^2	<0.0005	0.6691
R-Squared	0.9948	0.9810
Adj R-Squared	0.9881	0.9566
Pred R-Squared	0.9169	0.8962
Std. Dev.	0.6389	0.9778
Mean	34.7647	26.8059
C.V. %	1.8378	3.6477

$$Y = -1311.2500 + 5.1565X_1 + 18.1875X_2 + 1.9644X_3 - 0.0050X_1^2 - 5.6750X_2^2 - 0.0196X_3^2 \quad (4)$$

$$Y = -641.1219 + 2.9035X_1 - 11.6875X_2 - 0.4644X_3 - 3.7125X_2^2 \quad (5)$$

From the above equations and the significance study using p-value and F-test, it was observed that the parameters; reaction temperature and auger speed used had a direct effect on the yield while, no interactive effect was seen. In both feedstock, the linear effect of biomass to heat carrier ratio was seen to be negligible but, there was a significant quadratic effect observed.

The 3D plots for production of bio-crude using mesquite sawdust (Figure 6) showed the yield to increase up to 500 °C and 30 rpm auger speed and thereafter, declined. From the plot, it may be inferred that the optimum heat carrier to biomass ratio is 2:1 in this case. All the parameters are seen to be significant in the optimization of the yield either in the linear, interactive or quadratic term. Similar plots for rice straw (Figure 7) showed an increased efficiency at 475 °C then decreased with temperature. From the above results, we can infer that mesquite sawdust is the better feedstock for production of bio-crude from an auger reactor through pyrolysis.

3.5 Characterization

3.5.1 Thermogravimetric analysis

The thermogravimetric curves for rice straw at different temperatures are shown in Figure 2. At 350 °C and 400 °C, most of the hemicellulose has been removed. This difference agrees to the observed lower optimum pyrolysis temperatures for rice straw when compared to mesquite sawdust.

3.5.2 Physicochemical properties of the feedstock and organic phase

Both the feedstock and bio-crude, were made to undergo several analyses to study its suitability as a fuel. Such properties were density, proximate analysis, ultimate analysis and calorific value, as shown in Table 3. The initial moisture content of mesquite sawdust was 15.3 wt.% and 8.3 wt.% for rice straw. The bio-crude from both feedstocks at optimum conditions showed a reduced moisture content of 9.2 wt.% and 8.1 wt.%. While, this is promising for a better calorific value, the presence of moisture in bio-crude impairs usability as a

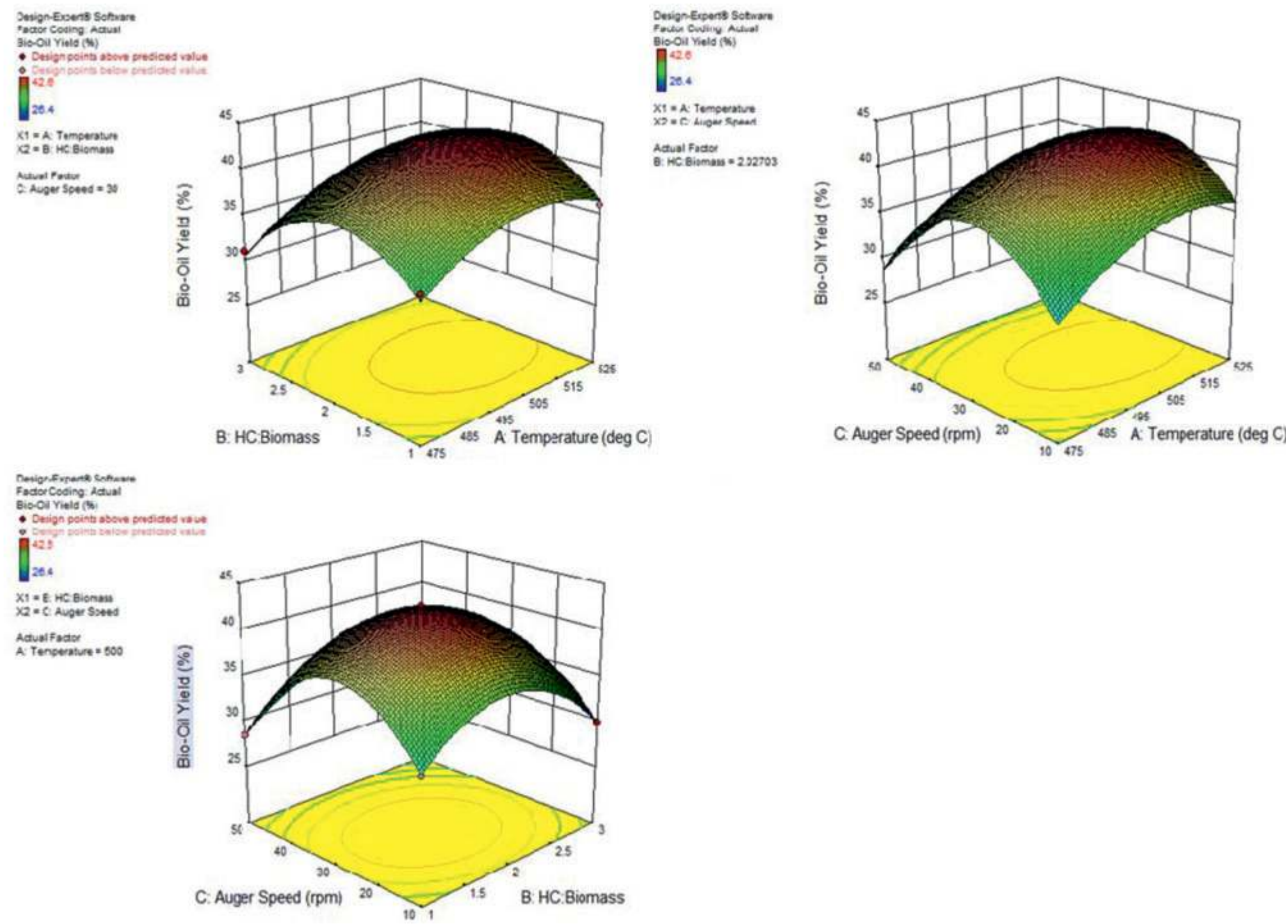

Figure 6: 3D contour plots from bio-crude production from mesquite sawdust.

fuel in transportation. Other bio-oil properties were also upgraded. The observed density for bio-crude from sawdust was 1209 kg/m^3 and 1326 kg/m^3 for rice straw. High density and viscosity values could lead to problems related to pressure drops, poor atomization and increasing pumping costs. Although water addition could contribute to reduce viscosity and to improve stability, it also reduces heating value (Bridgwater 2012). Similar trends were observed by Yathavan and Agblevor for biomass pyrolysis in a fluidized bed reactor (Yathavan and Agblevor 2013). Obtained bio-crude also presented the advantages of having negligible percentages of S and N (Table 3), as expected taking into account the composition of the raw materials. It was also shown that there is lower oxygen content in raw sawdust (43.16 wt.%) when compared to rice straw (45.98 wt.%). Moreover, pyrolysis led to a definite reduction in the O_2 percentage, likely related to a lower percentage of water. Unfortunately, O_2 percentage is still higher than that found in conventional fuel (Bridgwater 2012).

Overall, a slight rise in the HHV of the bio-crude was observed, when compared to the raw materials for each feedstock studied, in agreement with its higher carbon composition and lower water content. The obtained heating value is still lower than petroleum fuel. In any event, the heating value of typical bio-crude is less than half (dry organic basis) of petroleum fuel, and the most relevant consequence is that higher quantities of bio-crude are required (Lehto et al. 2014) for a given throughput.

4 Conclusion

Auger pyrolyzer experiments revealed the influence of heat carrier temperature, auger speed and reaction

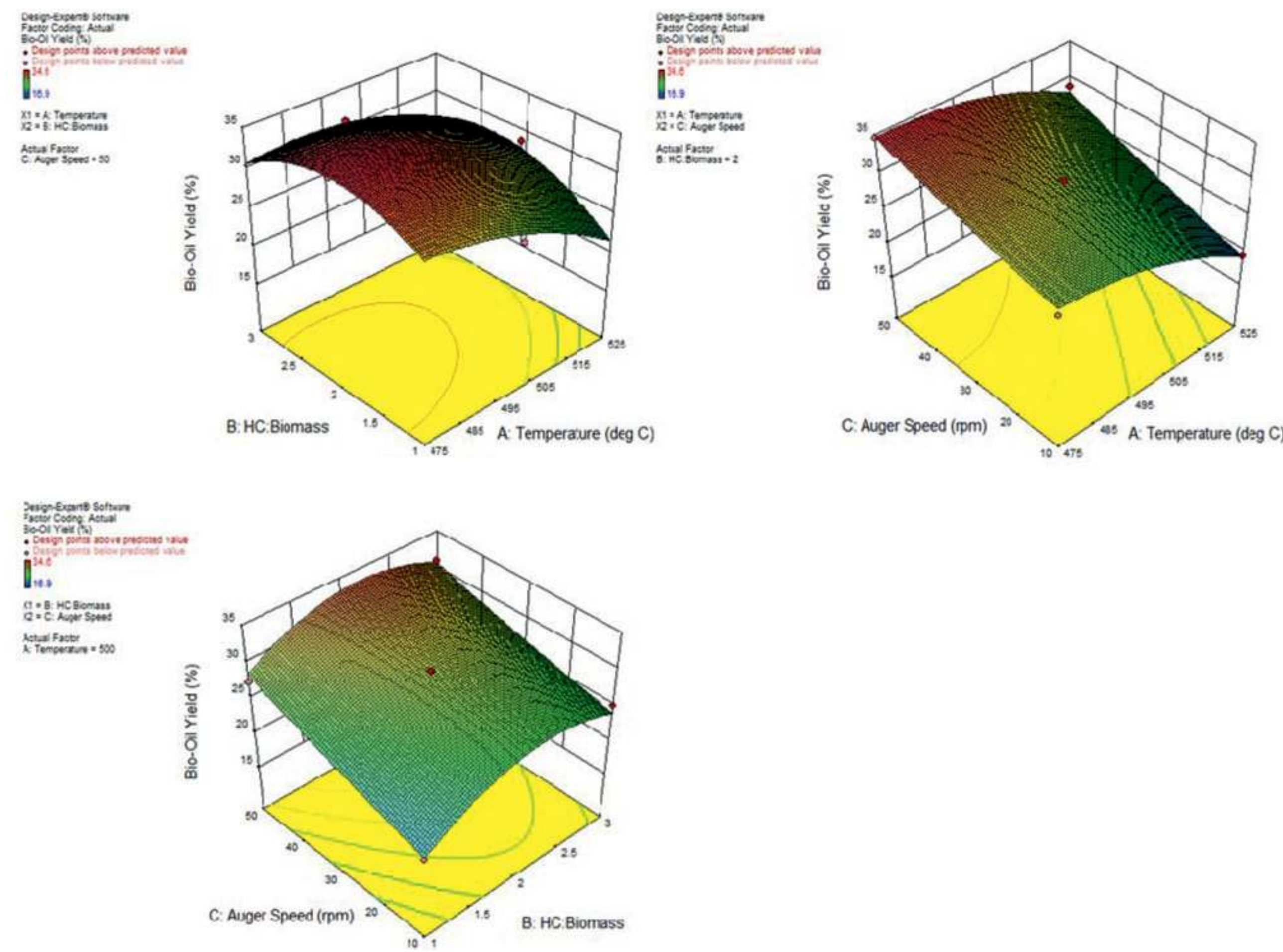

Figure 7: 3D contour plots from bio-crude production from rice straw.

temperature on bio-crude yield. Yield models revealed a definite effect for temperature and auger speed for both mesquite sawdust and rice straw. An optimum reaction temperature was observed for sawdust at 500 °C and 475 °C for straw. Using a heat carrier assures rapid heat transfer to biomass. A definite high throughput was observed from both feedstocks with quality at par with reported literature.

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References

1. Azargohar, R., Nanda, S., Kozinski, J.A., Dalai, A.K., Sutarto, R., 2014. Effects of temperature on the physicochemical characteristics of fast pyrolysis bio-chars derived from Canadian waste biomass. Fuel 125, 90–100. doi: 10.1016/j.fuel.2014.01.083.
2. Balagurumurthy, B., Srivastava, V., Vinit, Jitendra, K., Bijoy, B., Rawel, S., Piyush Gupta, K.L.N., Shiva, K., Singh, R., Bhaskar, T., 2015. Value addition to rice straw through pyrolysis in hydrogen and nitrogen environments. Bioresource Technology 188, 273–279. doi: 10.1016/j.biortech.2015.01.027.
3. Bridgwater, A.V., 2012. Review of fast pyrolysis of biomass and product upgrading. Biomass and Bioenergy 38, 68–94. doi: 10.1016/j.biombioe.2011.01.048.
4. Brown, J.N., Brown, R.C., 2012. Process optimization of an auger pyrolyzer with heat carrier using response surface methodology. Bioresource Technology 103(1), 405–414. doi: 10.1016/j.biortech.2011.09.117.
5. Chen, W., Kalyan Annamalai, R., Ansley, J., Mirik, M., 2012. Updraft fixed bed gasification of mesquite and juniper wood samples. Energy 41(1), 454–461. doi: 10.1016/j.energy.2012.02.052.
6. Chen, W., Thanapal, S.S., Annamalai, K., James Ansley, R., 2015. Liquid yield from juniper and mesquite bio-fuel

gasification. International Journal of Energy Research 39(5), 621–633. doi: 10.1002/er.3266.
7. Chen, Q., Yang, R., Zhao, Bo., Li, Y., Wang, S., Wu, H., Zhuo, Y., Chen, C., 2014. Investigation of heat of biomass pyrolysis and secondary reactions by simultaneous thermogravimetry and differential scanning calorimetry. Fuel 134, 467–476. doi: 10.1016/j.fuel.2014.05.092.
8. Cordella, M., Berrueco, C., Santarelli, F., Paterson, N., Kandiyoti, R., Millan, M., 2013. Yields and ageing of the liquids obtained by slow pyrolysis of sorghum, switchgrass and corn stalks. Journal of Analytical and Applied Pyrolysis 104, 316–324. doi: 10.1016/j.jaap.2013.07.001.
9. Fahmi, R., Bridgwater, A.V., Darvell, L.I., Jones, J.M., Yates, N., Thain, S., Donnison, I.S., 2007. The effect of alkali metals on combustion and pyrolysis of Lolium and Festuca grasses, switchgrass and willow. Fuel 86(10–11), 1560–1569. doi: 10.1016/j.fuel.2006.11.030.
10. Felger, R.S., Moser, M.B., 1971. Seri Use of Mesquite Prosopis Glandulosa Var Torreyana. The Kiva 37(34), 53–60.
11. Fernandez-Akarregi, A.R., Makibar, J., Lopez, G., Amutio, M., Olazar, M., 2013. Design and operation of a conical spouted bed reactor pilot plant (25 kg/h) for biomass fast pyrolysis. Fuel Processing Technology 112, 48–56. doi: 10.1016/j.fuproc.2013.02.022.
12. Francis, W., Peters, M.C., 1980. Lurgi Pressure Gasification of Coal, Fuels and Fuel Technology, Pergamon Press, Inc., New York, ISBN:9781483147949.
13. Gadde, B., Menke, C., Wassmann, R., 2009. Rice straw as a renewable energy source in India, Thailand, and the Philippines: Overall potential and limitations for energy contribution and greenhouse gas mitigation. Biomass and Bioenergy 33(11), 1532–1546. doi: 10.1016/j.biombioe.2009.07.018.
14. Goyal, H.B., Seal, D., Saxena, R.C., 2008. Bio-fuels from thermochemical conversion of renewable resources: A review. Renewable and Sustainable Energy Reviews 12(2), 504–517. doi: 10.1016/j.rser.2006.07.014.
15. Guoxin, Hu., Xiwu, G., Hao, H., Haojie, F., Zheng, W., 2008. Experimental studies on flow and pyrolysis of coal with solid heat carrier in a modified rotating cone reactor. Chemical Engineering and Processing: Process Intensification 47(9–10), 1777–1785. doi: 10.1016/j.cep.2007.09.021.
16. Himmel, M.E., Ding, S.Y., Johnson, D.K., Adney, W.S., Nimlos, M.R., Brady, J.W., Foust, T.D., 2007. Biomass Recalcitrance: Engineering Plants and Enzymes for Biofuels Production. Science 315(5813), 804–807. doi: 10.1126/science.1137016.
17. Horne, P.A., Williams, P.T., 1996. Influence of temperature on the products from the flash pyrolysis of biomass. Fuel 75(9), 1051–1059. doi: 10.1016/0016-2361(96)00081-6.
18. Houghton, J., Weatherwax, S., Ferrell, J., 2006. Breaking the Biological Barriers to Cellulosic Ethanol: Biofuels Joint Road map for a US Dept of Energy Program: DOE/SC-0095, Publication Date: June 2006.
19. Johansson, A.-C., Wiinikka, H., Sandström, L., Marklund, M., Öhrman, O.G.W., Narvesjö, J., 2016. Characterization of pyrolysis products produced from different Nordic biomass types in a cyclone pilot plant. Fuel Processing Technology 146, 9–19. doi: 10.1016/j.fuproc.2016.02.006.
20. Kohl, T., Laukkanen, T.P., Järvinen, M.P., 2014. Integration of biomass fast pyrolysis and precedent feedstock steam drying with a municipal combined heat and power plant. Biomass and Bioenergy 71, 413–430. doi: 10.1016/j.biombioe.2014.09.014.
21. Körbahti, B.K., Rauf, M.A., 2008. Application of response surface analysis to the photolytic degradation of Basic Red 2 dye. Chemical Engineering Journal 138(1–3), 166-171. doi: 10.1016/j.cej.2007.06.016.
22. Kothari, K., Shah, A.B., Murugavelh, S., 2015. Bio Oil Production: Pyrolysis of Saw Dust in an Auger Reactor. International Journal of ChemTech Research 8(6), 349–357.
23. Lehto, J., Oasmaa, A., Solantausta, Y., Kytö, M., Chiaramonti, D., 2014. Review of fuel oil quality and combustion of fast pyrolysis bio-oils from lignocellulosic biomass. Applied Energy 116, 178–190. doi: 10.1016/j.apenergy.2013.11.040.
24. Liaw, S.-S., Shuai, Z., Wu, H., Garcia-Perez, M., 2013. Effect of pretreatment temperature on the yield and properties of bio-oils obtained from the auger pyrolysis of Douglas fir wood. Fuel 103, 672–682. doi: 10.1016/j.fuel.2012.08.016.
25. Luo, Z., Wang, S., Liao, Y., Zhou, J., Gu, Y., Cen, K., 2004. Research on biomass fast pyrolysis for liquid fuel. Biomass and Bioenergy 26(5), 455–462. doi: 10.1016/j.biombioe.2003.04.001.
26. Ma, Z., Gao, N., Xie, L., Li, A., 2014. Study of the fast pyrolysis of oilfield sludge with solid heat carrier in a rotary kiln for pyrolytic oil production. Journal of Analytical and Applied Pyrolysis 105, 183–190. doi: 10.1016/j.jaap.2013.11.003.
27. Mamaeva, A., Tahmasebi, A., Tian, Lu., Yu, J., 2016. Microwave-assisted catalytic pyrolysis of lignocellulosic biomass for production of phenolic-rich bio-oil. Bioresource Technology 211, 382–389. doi: 10.1016/j.biortech.2016.03.120.
28. Mi, B., Liu, Z., Hu, W., Wei, P., Jiang, Z., Fei, B., 2016. Investigating pyrolysis and combustion characteristics of torrefied bamboo, torrefied wood and their blends. Bioresource Technology 209, 50–55. doi: 10.1016/j.biortech.2016.02.087.
29. Moliner, C., Bosio, B., Arato, E., Ribes, A., 2016. Thermal and thermo-oxidative characterisation of rice straw for its use in energy valorisation processes. Fuel 180, 71–79. doi: 10.1016/j.fuel.2016.04.021.
30. Nam, H., Capareda, S.C., Ashwath, N., Kongkasawan, J., 2015. Experimental investigation of pyrolysis of rice straw using bench-scale auger, batch and fluidized bed reactors. Energy 93, 2384–2394.
31. Onay, O., 2007. Influence of pyrolysis temperature and heating rate on the production of bio-oil and char from safflower seed by pyrolysis, using a well-swept fixed-bed reactor. Fuel Processing Technology 88(5),523–531. doi: 10.1016/j.fuproc.2007.01.001.
32. Patwardhan, P.R., Dalluge, D.L., Shanks, B.H., Brown, R.C., 2011. Distinguishing primary and secondary reactions of cellulose pyrolysis. Bioresource Technology 102(8), 5265–5269. doi: 10.1016/j.biortech.2011.02.018.
33. Piekarczyk, W., Czarnowska, L., Ptasiński, K., Stanek, W., 2013. Thermodynamic evaluation of biomass-to-biofuels production systems. Energy 62, 95–104. doi: 10.1016/j.energy.2013.06.072.
34. Pillai, M.G., Regupathi, I., Helen Kalavathy, M., Murugesan, T., Miranda, L.R., 2009. Optimization and analysis of nickel adsorption on microwave irradiated rice husk using response surface methodology (RSM. Journal of Chemical Technology and Biotechnology 84(2), 291–301. doi: 10.1002/jctb.2038.

35. Pilon, G., Lavoie, J.-M., 2013. Pyrolysis of switchgrass (Panicum virgatum L.) at low temperatures in N2 and CO2 environments; a study on chemical composition of chars extracts and bio-oils. Journal of Analytical and Applied Pyrolysis 101, 122–131. doi: 10.1016/j.jaap.2013.02.002.
36. Restrepo, Á., Bazzo, E., 2016. Co-firing: An exergoenvironmental analysis applied to power plants modified for burning coal and rice straw. Renewable Energy 91, 107–119. doi: 10.1016/j.renene.2016.01.048.
37. Salehi, E., Abedi, J., Harding, T.G., Seyedeyn-Azad, F., 2013. Bio-oil from sawdust: Design, operation, and performance of a bench-scale fluidized-bed pyrolysis plant. Energy & Fuels 27 (6), 3332–3340.
38. Subahana, K.R., Natarajan, R., 2016. Theoretical modelling and experimental investigation of the convective drying kinetics of biomass in an improved solar tunnel dryer. Biofuels, 1–8. doi: 10.1080/17597269.2015.1132372.
39. Subahana, K.R., Natarajan, R., Awasthi, A., Mathew, M., Gangadharan, M.N., 2006. The thin layer drying characterstics of chilly leaf under open sun and in a solar dryer.
40. Sulaiman, F., Abdullah, N., 2011. Optimum conditions for maximising pyrolysis liquids of oil palm empty fruit bunches. Energy 36(5), 2352–2359. doi: 10.1016/j.energy.2010.12.067.
41. Tian, L., Shen, B., Xu, H., Li, F., Wang, Y., Singh, S., 2016. Thermal behavior of waste tea pyrolysis by TG-FTIR analysis. Energy 103, 533–542. doi: 10.1016/j.energy.2016.03.022.
42. Tsai, W.T., Lee, M.K., Chang, Y.M., 2006. Fast pyrolysis of rice straw, sugarcane bagasse and coconut shell in an induction-heating reactor. Journal of Analytical and Applied Pyrolysis 76 (1–2), 230–237. doi: 10.1016/j.jaap.2005.11.007.
43. Veses, A., Aznar, M., Callén, M.S., Murillo, R., García, T., 2016. An integrated process for the production of lignocellulosic biomass pyrolysis oils using calcined limestone as a heat carrier with catalytic properties. Fuel 181, 430–437. doi: 10.1016/j.fuel.2016.05.006.
44. Wang, P., Zhan, S., Yu, H., Xue, X., Hong, N., 2010. The effects of temperature and catalysts on the pyrolysis of industrial wastes (herb residue. Bioresource Technology 101(9), 3236–3241. doi: 10.1016/j.biortech.2009.12.082.
45. Wu, X., Zhang, J., Xu, E., Liu, Y., Cheng, Y., Addy, M., Zhou, W., Griffith, R., Chen, P., Ruan, R., 2016. Microbial hydrolysis and fermentation of rice straw for ethanol production. Fuel 180, 679–686. doi: 10.1016/j.fuel.2016.04.087.
46. Yang, Z., Sarkar, M., Kumar, A., Tumuluru, J.S., Huhnke, R.L., 2014. Effects of torrefaction and densification on switchgrass pyrolysis products. Bioresource Technology 174, 266–273. doi: 10.1016/j.biortech.2014.10.032.
47. Yang, H., Yan, R., Chen, H., Lee, D.H., Zheng, C., 2007. Characteristics of hemicellulose, cellulose and lignin pyrolysis. Fuel 86(12–13), 1781–1788. doi: 10.1016/j.fuel.2006.12.013.
48. Yathavan, B.K., Agblevor, F.A., 2013. Catalytic Pyrolysis of Pinyon–Juniper Using Red Mud and HZSM-5. Energy & Fuels 27 (11), 6858–6865. doi: 10.1021/ef401853a.
49. Zheng, Mo., Wang, Ze., Li, X., Qiao, X., Song, W., Guo, Li., 2016. Initial reaction mechanisms of cellulose pyrolysis revealed by ReaxFF molecular dynamics. Fuel 177, 130–141. doi: 10.1016/j.fuel.2016.03.008.