Plant Archives **Vol. 25, Special Issue (ICTPAIRS-JAU, Junagadh) Jan. 2025 pp. 691-697**
e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2025.SP.ICTPAIRS-099

EXPERIMENTAL INVESTIGATION ON OPEN-CORE DOWNDRAFT GASIFIER FOR BIO-CHAR PRODUCTION AND GASEOUS FUEL FROM CASTOR STALK

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ABSTRACT

In this investigation, the researchers designed and developed an 80 MJ/h downdraft gasifier reactor and examined the gasification process of shredded castor stalks. To assess the gasifier's performance, trials were conducted at flow rates of 20 m^3/h, 22 m^3/h and 24 m^3/h, respectively. The findings indicated the optimal performance of the gasifier at 22 m^3/h with an equivalence ratio of 0.31. Gasification efficiency was recorded at 71.44%, with a specific gasification rate of 225.32 kg/hm^2. Moreover, the particular gas production rate was determined to be 556.96 ^{m3}/hm^2. The gasifier yielded residual bio-char totalling 22.02% and exhibited a calorific value of 1180 kcal/m^3. The fuel consumption rate was calculated at 8.90 kg/h. These results suggest that shredded castor stalks hold potential as fuel in throat less downdraft gasifiers, leading to producing producer gas.

Key words : Biomass, Gasification, Bio-char, Open core downdraft gasifier, Castor stalk.

Introduction

In India 21st century, Energy and Pollution are important concerns for the world. The energy demand is increasing because of economic empowerment. Sustainable energy solution is one of the most important challenges posed before mankind. Renewable energy technologies can provide a viable solution to the demand for energy production and pollution reduction leading to mitigation of adverse effect of global warming and climate change. Agricultural wastes, algae biomass, crop residues, animal wastes, activated sludge, energy crops and digestate are the primary sources of biomass as a feedstock (Li *et al.*, 2020; Raud *et al.*, 2019). Many physical, thermochemical, and biochemical methods can be used to turn biomass into high-value products. Bio-char is derived through thermo- chemical conversions of carbonaceous biomass at elevated temperatures (300–900 °C) and in limited oxygen conditions, including pyrolysis, gasification, Torrefaction, and hydrothermal carbonization (HTC) (Nidheesh *et al.*, 2021).

Castor is one of the oldest cultivated crops. The oil produced from this crop is considered to be of importance to the global speciality chemical industry because it is the only commercial source of hydroxylated fatty acid. Castor plant is grown in arid and semi-arid regions. In 2020-21, World major producing countries is India (16.47 lakh tonnes). Gujarat is the leading producer of castor in India, accounting for over 80% of the country's total production. In 2023-24, Gujarat produced 15.13 lakh tonnes of castor, while the rest of India produced 3.49 lakh tonnes.

Biomass utilization is a rapidly growing sector of renewable. Worldwide, biomass is the fourth most used fuel after oil, coal and natural gas. Though most biomass usage in the developing world is in thermal applications, especially for cooking, the sector is increasingly modernizing to provide efficient secondary energy forms such as liquid fuels and electricity. Castor stalk and other agricultural crop residues are available in plenty and have potential as an energy source in this region. These residues are sometimes burnt in the field itself, creating adverse soil health conditions. Considering the above background, the present study is undertaken on the open-core gasification of shredded Castor stalk for bio-char production. The producer gas is used for thermal application and the bio-char can be used for soil amendments, water purification and activated bio-char which depends on its properties. The process of converting a solid fuel thermochemically into gas using gasification technology uses less air than is necessary for burning. The ability to process a range of inputs, including fuel, coco and waste, the ability to convert low-value biomass into higher-value products, the ability to reduce the amount of solid waste while producing safe and harmless gas, and the ability to produce a product as consistent as a power plan are just a few of the many benefits of gasification technologies (Jenkins, 1999).

Materials and Methods

Experimental details

The experimental setup consists of an open-core throat less downdraft gasifier with a cyclone separator, tar separator and cooling tower developed at the Department of Renewable Energy Engineering, CAET, JAU, Junagadh with a capacity of 80 MJ/h. Fig. 1 shows the developed open-core throat less downdraft gasifier. Feeding of shredded biomass is carried out at the top of the reactor

Fig. 1 : Developed open-core throat less downdraft gasifier.

Physical Properties of Whole Castor Stalk

Physical properties of whole and shredded Castor stalk were determined in terms of average length, diameter and bulk density. The average length of 15 pieces of randomly selected whole Castor plant stalks were measured with the help of measure tap. Average diameter of 15 pieces of randomly selected whole Castor plant stalks were measured with the help of Vernier caliper. The bulk density of whole Castor stalk plant was also measured. The bulk density of whole Castor plant was determined by tying the plant with the help of ropes with gentle rolling and pressing, so as to consider the bunch as cylinder. Weight of the bunch was measured with the help of spring balance. The bulk density is the weight of biomass bunch divided by the volume occupied by Castor stalk bunch.

Material preparation

In this study, shredded castor stalk was used as feed material and the shredder was used for the shredding operation available at the department. It mainly consists of feeding trough, peg tooth beater, outlet section, electric motor and stand. The shredder is operated with the help of 10 hp, 3 phase and 1450 rpm electric motor. The capacity of shredder machine was 250 kg/h.

Physical Properties of Shredded Castor Stalk Biomass and its Bio-char

Different size fractions shredded Castor stalk were analyzed in terms of weight and length. Three samples of randomly selected, 2 kg shredded Castor stalk biomass was considered for the analyses. Each sample was divided into seven fractions i.e. (1) thick, having diameter ranging from 13-20 mm, (2) medium, having diameter 9-12.99 mm, (3) thin, having diameter 4-8.99 mm, (4) very thin, having diameter 2-3.99 mm, (5) very fine having diameter less than 2 mm, material passed through 2 mm sieve. It was shown in Fig. 2. The diameter of each fraction of shredded Castor stalk was measured with the help of Vernier caliper. The maximum and minimum length of each fraction of shredded material was also measured with the help of scale. Five fractions i.e. thick, medium, thin were separated manually. Remaining samples were sieved through 2 mm sieve. The material retained in the sieve was considered as thin material and passed through, it was considered as very fine thin material. Each sample of the shredding material was weighed using a weighing balance (Metler pe-3600) having capacity and least count of 3.6 kg and 0.01g, respectively. The bulk density of shredded Castor and Pigeon pea stalk was determined by the weight of biomass placed in a container & divided by the analysis occupied. Different size fraction of bio-char of shredded Castor stalk were also analyzed in terms of weight and length. Three samples of randomly selected, 1 kg bio-char of shredded Castor stalk obtained from each experiment run were used for the analysis. The bio-char was manually sieved through the sieves of 3 × 3 (nearly 7 mm × 7 mm square opening), 4 × 4 (nearly 5.5 mm × 5.5 mm square opening), 6 × 6 (nearly 3.5 mm × 3.5 mm square opening), and 10 × 10 (nearly 1.5 mm × 1.5 mm square opening) screen opening, respectively. The material retained in passed through each subsequent sieve were considered as total five different size fractions. Each size fraction was weighed and measured randomly for its minimum and maximum length as considered in the case of shredded Castor stalk.

Proximate analysis of Castor Stalk and its Bio-char

Proximate analysis characterizes the biomass feedstock for its ash content, volatile matter and fixed carbon. Proximate analysis of Castor and Pigeon pea stalk and its bio char is determined as per the following methods. Proximate analysis of the fuel defines its volatility and burning properties. ASTM standard (ASTM E870-82, 2013) recommended for coal, sparkly fuels, etc., which meets the demand of the biomass material largely, were used for this analysis.

Results and Discussion

Physical properties of whole Castor and Pigeon pea Stalk biomass

Average length and diameter of each section, average diameter and bulk density of whole Castor and Pigeon pea stalk is shown in Table 1.

Physical properties of Shredded Castor Stalk Biomass

Physical properties of shredded Castor and Pigeon pea stalk were measured. Table 2 shows the different size fractions of shredded Castor stalk biomass in terms of average weight, % weight and minimum-maximum lengths of shredded Castor stalk. The values of different size fractions of randomly selected three samples of 2000g shredded Castor stalk along with bulk density were determined. Different size fraction of bio-char of shredded cotton stalk were also analysed in terms of weight and length (Makavana *et al.*, 2022).

Proximate analysis of Shredded Castor Stalk biomass

Table 3 shows the proximate analysis of Castor stalk biomass. The moisture content of the Castor stalk biomass was found as 11.90 percent dry basis, which represented the suitability of fuel for gasification in down draft gasification systems. The fixed carbon, volatile matter, ash content and Calorific Value were found as 19.07, 72.63, 8.30 (%, d.b), 04.08 (Kcal/kg) respectively for Castor stalk.

Proximate analysis of shredded castor stalk bio-char

Table 4 shows the proximate analysis of Castor stalk bio-char at different gas flow rates. The ash content, volatile mater content, fixed carbon content and volatile matter/fixed carbon ratio of the Castor stalk bio-char was found as 11.21, 15.35, 13.64, 25.98, 25.12, 30.03, 62.81, 59.61, 56.33 percent dry basis. Volatile matter/fixed carbon ratio of the Castor and Pigeon pea stalk bio-char was found as 0.31, 0.42 and 0.53, 0.53, respectively. The quality of bio-char is largely determined by its fixed carbon content. The volatile matter content in the biomass is (per definition) excluded from its fixed carbon content, but may under certain conditions contribute to the fixed carbon content in the product (Kathrin Weber and Peter Quicker, 2018).

Table 1 : Physical properties of whole Castor stalk biomass.

S. no.	Average length, mm	Average diameter of sections, mm			Average diameter of whole Castor and Pigeon pea stalk, mm	Bulk density, gm/cc
		Lower section (0 -500mm)	Middle section (500–1000mm)	Upper section (> 1000mm)		
Castor	2400	40.12	28.61	19.56	29.43	0.288

Table 2 : Different size fractions of shredded Castor stalk biomass.

S. no.	Size fraction	Castor stalk			
		Average weight		Length, mm	
		g	%	min	max
1.	Thick,(13-20 mm diameter)	490.0	24.5	33.0	320.0
2.	Medium, (9-12.99 mm diameter)	440.0	22.0	28.0	273.0
3.	Thin,(4-8.99mm diameter)	380.0	19.0	30.0	186.0
4.	Very Thin, (2-3.99 mm diameter)	410.0	20.5	18.0	170.0
5.	Fine, (less than 2 mm diameter)	280.0	14.0	7.0	9.0
	Total	2000.0	100.0	-	-

Elemental analysis of castor stalk bio-char at different gas flow rate

Table 5 shows the Elemental Analysis of Castor stalk biomass stalk bio-char in terms of nitrogen (N), carbon (C), hydrogen (H), oxygen (O) and sulphur (S) were determined for all the experimental runs.

The analysis of Castor stalk biomass in terms of nitrogen (N), carbon (C), hydrogen (H), oxygen (O) and sulphur (S) was found 0.88, 43.13, 6.28, 19.49, 0.12%, respectively. (Tanquilut *et. al.* 2019) was found the similar values of Carbone (%) of pigeon pea stalk. One main

Table 3 : Proximate analysis of Castor stalk biomass.

S. no.	Moisture Content, % d.b	Fixed carbon, % d.b	Volatile matter, % d.b	Ash content, %, d.b	Calorific value (Kcal/ kg)
Castor stalk	11.90	19.07	72.63	08.30	04.08

Table 4 : Proximate analysis of shredded Castor stalk bio-char.

Particular	Castor stalk Bio-char		
	$20m^3/h$	$22m^3/h$	$24m^3/h$
Ash content, % d.b	11.21	15.38	13.64
Volatile matter content, % d.b	25.98	25.12	30.03
Fixed carbon content, % d.b	62.81	59.61	56.33
Volatile matter/Fixed carbon ratio	0.31	0.42	0.53

Table 5 : Elemental Analysis of Castor stalk biomass.

Particular	Castor stalk
Nitrogen (%)	0.88
Carbon (%)	43.13
Hydrogen (%)	6.28
Oxygen (%)	19.49
Sulphur (%)	0.12

*NABL approved laboratory.

Table 6 : Elemental Analysis of Castor stalk bio-char at different gas flow rates.

Particular	Castor Bio-char		
	Value at different gas flow rate		
	$20m^3/h$	$22m^3/h$	$24m^3/h$
Nitrogen (%)	1.03	1.10	1.05
Carbon (%)	56.50	65.16	58.95
Hydrogen (%)	3.00	3.28	3.12
Oxygen (%)	8.03	7.33	7.79
Sulphur (%)	0.17	0.15	0.16

Table 7 : Different size fractions of shredded Castor stalk bio-char.

Size fractions	Castor Bio-char			
	Average weight		Length, mm	
	g	%	Min	Max
Large (more than 4.76 mm)	203.50	20.35	18.00	98.00
Medium (4.00 – 4.76 mm)	180.51	18.05	13.00	65.00
Small (2.38 – 4.00 mm)	195.90	19.59	10.00	42.00
Thin (2.00 – 2.38 mm)	315.11	31.51	8.00	29.00
Powder (less than 2 mm)	104.98	10.50	-	-
Total	**1000.00**	**100.00**	-	-

goal of bio-char production is the change in chemical composition compared to that of raw biomass, most of all the increase in carbon content. This is due to the detachment of functional groups, containing oxygen and hydrogen. Therefore, an increase in reaction temperature leads to an increase in carbon content while resulting in a lower content of hydrogen and oxygen. This can be seen in Table 6 (Kathrin Weber and Peter Quicker, 2018).

The NABL approved laboratory analysis of Castor stalk bio-char in terms of nitrogen (N), carbon (C), hydrogen (H), oxygen (O) and sulphur (S) was found 1.03, 1.10, 1.05, 56.50, 65.16, 58. 95, 3.00, 3.28, 3.12, 8.03, 7.33, 7.79, 0.17, 0.15, 0.16%, respectively.

Physical properties and chemical properties of shredded castor stalk bio-char

The fractions of shredded Castor stalk bio-char were divided into five different size fractions i.e. large, material retained in 4 mesh sieve (4.76 mm opening), medium, material retained in 5 mesh sieve (4.00 mm opening), small, material retained in 8 mesh sieve (2.38 mm opening), thin, material retained in 9 mesh sieve (2.00 mm opening) and powder (less than 2 mm) as the material passed through 9 mesh opening sieve. Table 7 shows the average values of different size fractions of the bio-char and minimum and maximum length of the bio-char.

Chemical analysis of shredded Castor stalk and its bio-char obtained during the open core gasification at different gas flow rates were carried out in terms of pH, electrical conductivity (EC), organic carbon, N, P_2O_5, K_2O, S and cation exchange capacity (CEC). Tables 8 and 9 shows the chemical properties of shredded Castor stalk and its bio-char.

It can also be seen from the table that the values of EC (1:10), pH (1:10), CEC (me/100gm), available N, available P_2O_5, available K_2O, available S (ppm) and Water holding capacity (%) of shredded Castor stalk were found as 1.94, 5.60, 28.31, 0.067, 0.050, 0.110, 42.27, 542.23%, respectively.

Chemical analysis of shredded Castor stalk bio-char obtained during the open core gasification at different gas flow rates were carried out in terms of EC (1:10), pH (1:10), CEC (me/100gm), N, P_2O_5, K_2O and S. the values of available N, available P_2O_5, available K_2O and available S (ppm) of shredded Castor stalk bio-char were found as different gas flow rate $20m^3/h$, $22m^3/h$ and $24m^3/h$. 5.58, 4.62 and 4.87. A direct result of the increasing alkalinity is an increasing pH-value of bio-char. The pH-value of bio-char is an important property for agricultural

Table 8 : Chemical properties of shredded Castor and Pigeon pea stalk.

Particular	Castor stalk
EC(ds/m)	1.94
pH(1:10)	5.60
CEC (me/100gm)	28.31
Available N, %	0.067
Available P_2O_5, %	0.050
Available K_2O, %	0.110
Available S,(ppm)	42.27
Water holding capacity (%)	542.23

* NABL approved laboratory.

Table 9 : Chemical properties of Castor stalk bio-char at different gas flow rates.

Particular	Shredded Castor Stalk Bio-char		
	Value at different gas flow rate		
	20m³/h	22m³/h	24m³/h
EC(ds/m)	05.58	04.62	04.87
pH (1:10)	10.28	10.49	10.65
CEC (me/100gm)	42.36	47.96	49.13
Available N, %	0.73	01.10	0.78
Available P_2O_5, %	0.14	0.15	0.19
Available K_2O, %	0.58	0.59	0.66
Available S,(ppm)	92.66	102.95	126.36
Calorific Value (Kcal/ kg)	04.37	06.13	08.14
Bulk density (kg/ m³)	189	193	201
Water holding capacity (%)	500.64	484.59	461.47

* NABL approved laboratory.

Table 10 : Fuel consumption and air flow rate during the gasification at different gas flow rates.

Gas flow rate, m³/h	Castor stalk	
	Air flow rate, m³/h	Fuel consumption, kg/h
20	9.03	7.20
22	12.46	8.90
24	20.01	10.25

applications such as soil amendment. The values 10.28, 10.49 and 10.65. Values of CEC 42.36, 47.96 and 49.13 respectively. similar results found 50.11, 0.73 and 0.63, 1.10 and 0.70, 0.78 and 0.71. Lee (2010) found cation exchange capacity (CEC) is the amount of exchangeable cations (e.g. Ca_2^+, Mg^{2+}, K^+, Na^+, NH_4^+). Available P_2O_5

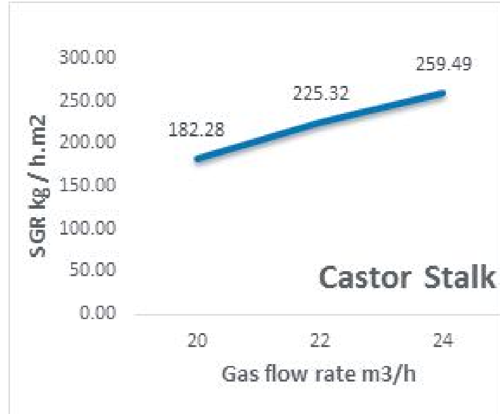

Fig. 2 : Variation of specific gasification rate with gas flow rate for Castor stalk.

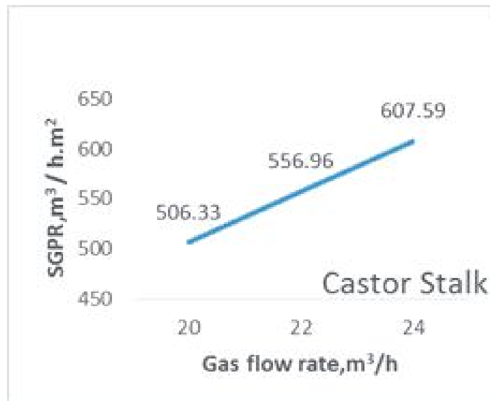

Fig. 3 : Variation of specific gas production rate with gas flow rate for Castor stalk.

0.14, 0.15, 0.19, 0.58, 0.59 and 0.66 % respectively. 92.66, 102.95 and 126.36 ppm, respectively. Also can found the calorific value (Kcal/ kg), Bulk density (kg/ m³) and Water holding capacity (%) of bio-char 04.37, 06.13 and 08.14 respectively 189, 193 and 201, 500.64, 484.59 and 461.47, respectively. Percentage of nitrogen content increased with increase in gas flow rate because, as the temperature increases, volatiles are driven off resulting in an overall decrease in mass (Makavana *et al.*, 2024 and Makavana *et al.*, 2020) found that the bulk density of whole cotton stalk and shredded cotton stalk was 29.90 kg/m³ and 147.02 kg/m³, respectively, indicating a 3.91-fold increase in density upon shredding. The bulk density of shredded cotton stalk was determined by the weight of biomass placed in a container & divided by the analysis occupied. Development of batch type biomass pyrolyser for agricultural residue (Makavana and Sarsavadiya, 2018.). Bulk density of rice husk and rice straw was 331.59 kg/m³ and 380.54 kg/m³ respectively. For sugarcane bagasse and cotton stalk it was 723.2 and 206.14kg/m³, respectively (Makavana *et al.*, 2018). The density of any bulk material is an important property for the design and operation of all handling and processing

Table 11 : Specific gasification rate, specific gas production rate and equivalence ratio at different gas flow rates.

Gas flow rate, m^3/h	Castor Stalk		
	SGR, $kg / h.m^2$	SGPR, $m^3 / h.m^2$	Equivalence ratio
20	182.28	506.33	0.24
22	225.32	556.96	0.31
24	259.49	607.59	0.39

facilities. While the weight-based energy density of bio-char increases with the treatment gas flow rate decreasing, the bulk density shows the opposite trend. As the gases devolatilize from the solid biomass structure during gasification, they leave a porous char behind. The higher the porosity, the lighter the char per unit volume becomes. Several different densities can be distinguished: The bulk density considers the volume specific weight of a bulk material in a heap or pile and includes both the pores in the solid structure as well as the voids between different particles of the bulk. The envelope density takes the solid structure, all pores and surface irregularities into account. It is based on a single particle and therefore disregards voids in the bulk (Kathrin Weber and Peter Quicker, 2018). As a result of the higher carbon content in the bio-char, the energy content increases with temperature. Table 9 shows this correlation for shredded Castor and Pigeon pea stalk like as a feed stocks.

Performance of open core down draft biomass gasifier

Performance of the gasifier was carried out at three different levels of gas flow rates (20, 22, and 24 m^3/h). The performance parameters in terms of fuel consumption rates (FCR), specific gasification rates (SGR), specific gas production rate (SGPR), equivalence ratio (ER), calorific value of producer gas, cold gasification efficiency, residual char and tar production were carried out at all the three levels of gas flow rates.

Fuel consumption rate and air flow rate

Fuel consumption and air flow rate during the gasification at different gas flow rates are shown in Table 10. The fuel consumption rate and air flow rate are increased with increase in gas flow rate. It is obvious that as the gas flow rate is increased, the air requirement is increased for the increase in gasification reaction rate with increase in fuel consumption rate.

Specific gasification rate and specific gas production rate

The values of specific gasification rate, specific gas production rate and equivalence ratio at different gas flow rates are shown in Table 11. It can also be seen from the Fig. 2 that the value of specific gasification rate is increased with increase in gas flow rate. It is also obviously seen from the figure that the behaviour is similar to that of the behaviour of fuel consumption with gas flow rate as seen in Fig. 2. The effect of gas flow rate on specific gas production rate is shown in Fig. 3. It can be seen from that the value of specific gas production rate is linearly increased with increase in gas flow rate.

Conclusion

Average bulk density of Proximate analysis of shredded Castor stalk was found as 0.880 and Bio-char 189, 193 and 182 (kg/ m^3), respectively. The moisture content of shredded Castor stalk was found as 11.90 (%, d.b). Calorific value of shredded Castor stalk and its bio-char was found 4.08 (Kcal/kg) and 4.37, 6.13, 8.14 (Kcal/kg), respectively. The values of fuel consumption rate and air flow rate were found as 7.20, 8.90, 10.25 kg/h and 9.30, 12.46, 20.01 m^3/h at different levels of gas flow rates of 20, 22 and 24m^3/h, respectively. The maximum value of gasification efficiency was found as 71.44 and 73.76% at the gas flow rate of 22m^3/h. The value of specific gasification rate and specific gas production rate was found as 182.28, 225.32, 259.49 kg/m^2h and 506.33, 556.96 and 607.59 $m^3/h\ m^2$ at different gas flow rates 20, 22 and 24m^3/h, respectively. Carbon content of shredded Castor stalk biomass and its bio-char was found as biomass 43.13 and 56.50, 65.16, 58.95%, respectively. The value of pH, EC and CEC of shredded Castor stalk biomass was found as 5.60 dS/m, 28.31 me/100gm, 0.99 dS/m, respectively.

Acknowledgement

The authors would like to thank CRP on Energy from Agriculture, ICAR - CIAE, Bhopal for their unwavering encouragement and support. The authors extend their gratefulness to the experts of Junagadh Agricultural University, Junagadh (Gujarat), India and ICAR, New Delhi for their timely financial assistance in the development and testing of the gasifier system.

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