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VALORIZATION OF VARIOUS AGRICULTURAL WASTE RESIDUES AND ITS BIO-CHAR PROPERTIES PRODUCED THROUGH GASIFICATION AND PYROLYSIS: A REVIEW

J.M. Makavana*, P.M. Chauhan, D.V. Patel, T.D. Mehta and M.J. Gojiya

Department of Renewable Energy Engineering, College of Agricultural Engineering and Technology, Junagadh Agricultural University, Junagadh - 362 001, Gujarat, India.

*Corresponding author E-mail : makavanajagu@gmail.com

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ABSTRACT

India has significant potential for producing bio-char due to the abundance of biomass resources. Numerous thermochemical and even biological techniques have been used to transform biomass into products with added value. Pyrolysis is the most practical of these processes since it offers a number of benefits for transportation, storage, and flexibility in solicitation, including turbines, combustion appliances, boilers, engines, etc. Fig. 1 shows the many types of current biomass conversion processes and their corresponding outputs. The study was conducted to look at the characteristics of various agricultural leftovers. Up until recently, the majority of BC's use in agriculture was around its use as a soil supplement. However, there are opportunities for further research in this broad area of study because there are many possible connections between different parameters, including but not limited to the BC's feedstock material, dose and its properties, type of soil, plant species and target elements/compounds of the treatment. The pyrolysis of agricultural waste to produce BC and BC-enhanced composting methods are two more related topics that have been researched.

Key words : Biomass, Bio-char, Pyrolysis, Waste material, Properties, Temperature.

Introduction

Bio-char production

Humans have been aware of the carbonization of wood for the creation of bio-char since the beginning of time. By making use of waste materials, improved bio-char technology can benefit humanity by meeting future energy needs and enhancing soil carbon sequestration capacity. The manufacture of bio-char involves four widely used technologies: fast pyrolysis, slow pyrolysis, carbonization and gasification.

Pyrolysis

It involves the thermochemical conversion of biomass in an environment with little or no oxygen. Depending on the process parameters, such as temperature, residence time, heating rate, and flow rate of sweeping gas, pyrolysis can be categorized into three general categories: fast, intermediate, and slow.

Bio-char, a highly porous charcoal-like material produced from organic waste through a process called pyrolysis, holds significant promise in agricultural and environmental applications. Its remarkable properties include high surface area, porosity, and ability to retain water and nutrients, making it a valuable soil amendment. However, despite its numerous benefits in improving soil fertility, enhancing crop yields and sequestering carbon, the utilization of bio-char in agricultural practices requires careful consideration and understanding of its potential impacts on soil ecosystems and crop productivity. Therefore, comprehensive research and implementation strategies are essential to harnessing the full potential of bio-char while mitigating any unintended consequences, ensuring sustainable agricultural practices and environmental stewardship. The quality of bio-char in terms calorific value (8101.3cal /gor 33.89MJ/kg), nitrogen (1.56), carbon (79.30), and C/N ratio (50.83)

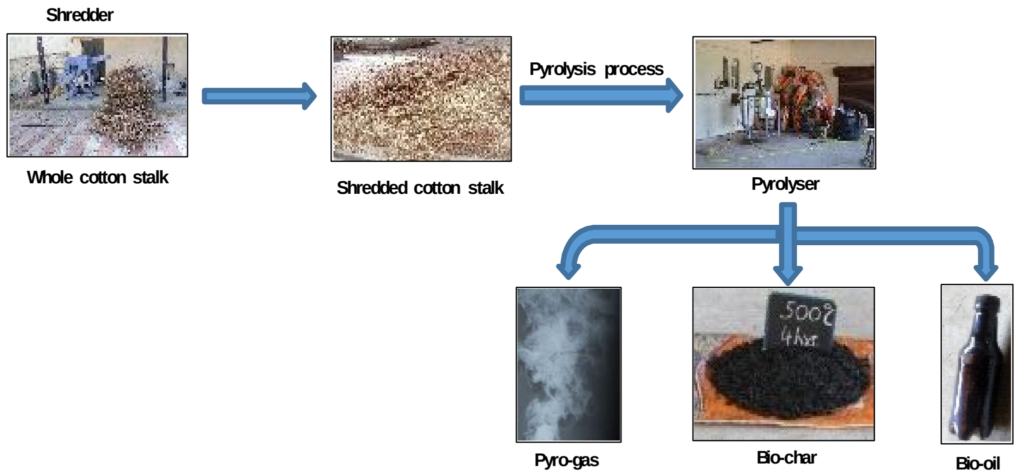

Fig. 1 : Overview of pyrolytic product (Makavana *et al*., 2020a).

Table 1 : Effect of temperature on various feedstock characteristics.

S. no.	Feedstock	Temp. (°C)	pH	VM (%)	FC (%)	Ash (%)	C (%)	H (%)	N (%)	O (%)	Ref.
1	Pig manure	200	8.22	50.70	12.60	35.70	-	-	-	-	Zhao *et al* (2013)
		300	-	-	-	-	-	-	-	-	
		400	-	-	-	-	-	-	-	-	
		500	10.50	11.00	40.20	48.40	-	-	-	-	
		600	-	-	-	-	-	-	-	-	
2	Wheat straw	200	5.43	70.20	22.50	7.21	-	-	-	-	Zhao *et al* (2013)
		300	-	-	-	-	-	-	-	-	
		400	-	-	-	-	-	-	-	-	
		500	10.20	17.60	63.70	18.00	-	-	-	-	
		600	-	-	-	-	-	-	-	-	
3	Pitch pine	200	-	-	-	-	-	-	-	-	Kim *et al* (2012)
		300	-	-	-	4.50	63.90	5.40	0.30	30.40	
		400	-	-	-	7.90	70.70	3.40	0.40	25.50	
		500	-	-	-	7.70	90.50	2.50	0.30	6.70	
		600	-	-	-	-	-	-	-	-	
4	Safflowerseed cake	200	-	-	-	-	-	-	-	-	Angin (2013)
		300	-	-	-	-	-	-	-	-	
		400	8.18	25.20	67.30	7.50	68.76	4.07	3.77	23.49	
		500	9.44	16.50	75.00	8.50	71.37	2.96	3.91	21.76	
		600	9.89	11.60	79.20	9.20	73.72	2.34	3.84	20.10	
5	Canocarpuswaste	200	7.37	-	-	4.53	64.19	3.96	0.69	26.61	Al-Wabel *et al* (2013)
		300	-	-	-	-	-	-	-	-	
		400	9.67	-	-	5.27	76.83	2.83	0.87	14.16	
		500	-	-	-	-	-	-	-	-	
		600	12.21	-	-	8.56	82.93	1.28	0.71	6.55	

Table 1 continued...

Table 1 continued...

S. no.	Feedstock	Temp. (°C)	pH	VM (%)	FC (%)	Ash (%)	C (%)	H (%)	N (%)	O (%)	Ref.
6	Rapeseed oil cake	200	-	-	-	-	-	-	-	-	Ucar *et al*. (2008)
		300	-	-	-	-	-	-	-	-	
		400	-	25.01	57.08	17.91	55.85	2.75	6.47	34.73	
		500	-	20.01	61.45	18.54	56.48	3.22	7.52	32.55	
		600	-	-	-	-	-	-	-	-	
7	Shreddedcotton stalk	200	5.88	79.48	15.02	5.5	-	-	-	-	Makavana *et al*. (2020)
		300	8.83	72.68	20.23	7.09	-	-	-	-	
		400	9.33	63.16	26.86	9.98	-	-	-	-	
		500	9.68	54.54	32.42	13.04	-	-	-	-	
		600	-	-	-	-	-	-	-	-	
8	Rice husk	200	-	-	—	-	-	-	-	-	YuehuiJia *et al*. (2018)
		300	-	-	-	64.19	-	-	-	-	
		400	-	-	-	66.06	-	-	-	-	
		500	-	-	—	66.56	-	-	-	-	
		600	-	-	-	75.35	-	-	-	-	
		700	-	-	-	76.20	-	-	-	-	
9	Cottonstraw (CS)	200	-	-	-	-	-	-	-	-	YuehuiJia *et al*. (2018)
		300	-	-	-	5.54	-	-	-	-	
		400	-	-	-	8.52	-	-	-	-	
		500	-	-	-	11.45	-	-	-	-	
		600	-	-	-	12.29	-	-	-	-	
		700	-	-	-	12.15	-	-	-	-	
10	Date seeds	350	6.9	-	-	6.7	64.4	-	-	-	Mahdi *et al*. (2017)
		350	8.6	-	-	-	82.2	-	-	-	
11	Pine woodchips	300	-	-	-	-	63.9	5.4	-	30.4	Kim *et al*. (2012)
		500	-	-	-	-	90.5	2.5	-	6.7	
12	Oxytreeprunings	200	-	-	-	-	38.1	7.2	4.6	42.4	Swiechowski *et al*. (2019)
13	Orange peels	300	8.0	-	-	3.9	41.9	6.4	1.8	47.9	
		700	12.3	-	-	-	-	-	0.7	-	
14	Residual wood	300	7.8	-	-	-	45.8	6.1	1.2	44.1	Oh *et al*. (2014)
		700	10.3	-	-	-	-	-	0.5	-	
15	Sawdust	200	-	-	-	0.7	-	-	-	-	Bialowiec *et al*. (2017)
		300	-	-	-	1.7	-	-	-	-	
16	Municipal waste	200	-	-	-	-	-	-	-	-	
		300	-	-	-	-	-	-	-	-	
17	Municipal waste	260	-	-	-	-	59.7	6.1	0.7	13.2	Bialowiec *et al*. (2018)

Table 1 continued...

Table 1 continued...

S. no.	Feedstock	Temp. (°C)	pH	VM (%)	FC (%)	Ash (%)	C (%)	H (%)	N (%)	O (%)	Ref.
18	Wastewater sludge	300	-	-	-	-	25.6	2.6	3.3	8.3	Hossain *et al.* (2010)
		700	-	-	-	-	20.2	0.5	1.2	-	
19	Sewage sludge	200	-	-	-	43	28.4	2.4	4.0	21.3	Pulka *et al.* (2019)
		300	-	-	-	73	12.7	0.7	2.7	9.0	
20	Poultry litter	300	-	-	-	48	38.0	-	-	-	Song and Guo (2011)
21	Poultry litter	450	9.9	-	-	-	38.0	2.0	-	-	Chan *et al.* (2008)
		550	13.0	-	-	-	33.0	0.9	-	-	
22	Brewer's spent grain	300	-	-	-	6.7	55.9	5.8	4.6	24.6	Dudek *et al* (2019)
23	Paddy straw	400	10.14	-	-	-	-	-	-	-	Novair *et al* (2023)

Table 2 : Fate of initial feedstock mass between products of pyrolysis processes (IEA, 2007).

Process	Liquid(bio-oil)	Solid(biochar)	Gas(syngas)
Moderate temperature (~500 °C) Short hot residence time (<2s)	75% (25% water)	12%	13%
Intermediate pyrolysis Low-moderate temperature, Moderate hot vapour residence time	50% (50% water)	25%	25%
Slow pyrolysis Low-moderate temperature, Long residence time	30% (70% water)	35%	35%
Gasification **High temperature (>800 °C)** **Long vapour residence time**	5% tar (5% water)	10%	85%

Table 3 : Various properties of agricultural residues.

	Bulk density kg/m³	True density kg/m³	Porosity	Angle of repose	Moisture content (%)	Ref.
Rice husk	331.59	1031.71	67.86	37.04	7.52	Makavana *et al.* (2018)
Rice straw	380.54	1671.97	77.24	38.23	9.89	
Sugarcane bagasse	723.2	4594.66	84.26	43.24	11.11	
Cotton stalk	206.14	507.36	59.37	43.18	10.01	
Pigeon pea stalk (shredded)	84.10	-	-	-	10.12	
Loos biomass	50-130	-	-	-	-	Sokhansanj *et al.* (2004)
Cotton stalk	99.28	-	-	-	-	Bhagwanrao and Singaravelu (2014)
Sunflower stalk	116.05	-	-	-	-	
Pigeon pea stalk	128.21	-	-	-	-	
Ground nut shell	98.95	-	-	-	-	
Cumbu Napier Grass	131.50	-	-	-	-	

Table 3 continued...

Table 3 continued...

	Bulk density kg/m³	True density kg/m³	Porosity	Angle of repose	Moisture content (%)	Ref.
Sawdust	300	-	-	-	-	Wu *et al*. (2011)
Chopped straw	60.00	-	-	-	-	
Green wood chips	500	-	-	-	-	
Cordwood	400	-	-	-	-	
Mustard stalk	141.63	-	-	-	8.83	Wakchaure *et al*. (2009)
Mixed waste	233.43	-	-	-	13.60	
Wood waste	251.30	-	-	-	8.64	
Corn stover	50.00	-	-	-	-	Thoreson *et al*. (2014)
Chopped corn stover	40-80	-	-	-	-	
Maize cobs	147.00	-	-	-	6.94	Singla *et al*. (2021)
Sesame Stalk	-	-	-	-	4.19	Gebresas *et al*. (2015)
Tree leaves	221.80	-	-	-	05.50	Wakchaure *et al*. (2007)
Saw dust	126.29	-	-	-	05.70	
Wheat straw	124.55	-	-	-	10.0	
Cotton stalk (powdered)	190	-	-	-	-	Kumar Sing *et al*. (2019)
Soybean stalk(powdered)	180	-	-	-	-	
Pigen pea stalk(powdered)	180	-	-	-	-	
Wheat straw	160.75	-	51.25	-	7.79	Major *et al*. (2012)
Rice straw	166.29	-	83.20	-	6.85	
Corn stalk	127.32	-	58.51	-	6.40	
Soybean stalk	242.34	-	68.03	-	7.30	
Sugarcane stalk	110.86	-	77.58	-	8.15	
Coffee husk	349.06	-	64.85	-	7.86	
Cotton stalk	230.55	-	74.55	-	7.45	
Pigeon pea wood	180	-	-	-	-	
Almond shells	450	-	-	-	-	Barisano *et al*. (2021)

Table 4 : Various agricultural residuesthermaland proximate properties.

Biomass materials	Calorific values Kcal/kg	Ash %	Volatile matter (%)	Fixed carbon (%)	Ref.
Arhar Stalk	4000	1.98	-	-	**Source: www.biopellet.in**
Babool Stalk	4650	0.99	-	-	
Bagasse	4380	10.8	-	-	
Bamboo Dust	4160	8.0	-	-	
Bark Wood	4270	4.4	-	-	
Black Wattle	4707	0.9	-	-	
Castor Seed Shell	3862	8.0	-	-	

Table 4 continued...

Table 4 continued...

Castor Stick	4300	5.4	-	-	
Cashew Husk	4100	20.0	-	-	
Coconut Waste	3720	6.31	-	-	
Coffee Husk	4045	3.2	-	-	
Coir Pith	4146	9.1	-	-	
Corn Cobs	3700	1.1	-	-	
Corn Dental Stick	4050	3.0	-	-	
Cotton Stalk & Shell	4252	4.6	-	-	
Eucalyptus Wood	4300	1.2	-	-	
Forestry Waste	3000	7.0	-	-	
Groundnut Shell	4524	3.8	-	-	
Jute Waste	4428	3.0	-	-	
Lemon Grass	4030	5.8	-	-	
Maize Stalk	4300	3.7	-	-	
Mulberry Stick	4380	2.49	-	-	
Mustard Shell	4300	3.7	-	-	
Mustard Stalk	4200	3.4	-	-	
Napier Grass	4051	8.55	-	-	
Paddy Straw	3436	15.5	-	-	
Palm Husk	3900	4.9	-	-	
Press Mud (Maili)	3600	14.25	-	-	
Rice Husk	3950	20.65	-	-	
Rice Straw	3200	21.2	-	-	
Saw Dust	4400	1.2	-	-	
Soya Bean Husk	4170	4.1	-	-	
Subabul Wood	4700	1.0	-	-	
Sugar Cane Leaves	4390	5.7	-	-	
Sun Flower Stalk	4100	4.3	-	-	
Sweet Sorghum Stalk	4100	7.4	-	-	
Tea Waste	4237	3.8	-	-	
Tobacco Waste	2910	31.5	-	-	
Wheat Straw	4100	6.4	-	-	
Wood Chips	4785	1.2	-	-	
Rice husk	-	18.60	70.70	10.70	Makavana *et al*. (2018)
Rice straw	-	15.20	64.43	20.37	
Sugarcane bagasse	-	3.28	86.15	10.62	
Cotton stalk	-	6.93	96.07	10.70	
Sesame Stalk	4152	4.16	77.11	14.54	Gebresas *et al*. (2015)
Almond shells	-	1.2	80.6	18.2	Barisano *et al*. (2021)
Pigeon pea wood	-	12.30	65.90	21.80	Makavana *et al*. (2022)

Table 5 : Physical properties and characteristics of bio-char from different feedstock.

S. no.	Feedstock	pH	Moisture (%)	Ash (%)	VM (%)	FC (%)	C (%)	H (%)	N (%)	O (%)	Reference
1	Safflowerseed cake	9.13	-	8.20	20.00	71.80	70.43	3.43	3.36	22.39	Angin (2013)
2	Conocarpuswastes	9.67	-	5.27	-	-	76.83	2.83	0.87	14.16	Al-Wabel *et al*. (2013)
3	Rice straw	9.68	7.20	15.40	62.40	14.90	44.80	5.10	0.90	49.20	Putun *et al*. (2004), Shenbagavalli and Mahimairaja (2012), Bakar *et al*. (2012)
4	Pitch pine	-	-	7.90	-	-	70.70	3.40	0.60	25.50	Kim *et al*. (2012)
5	Pine sawdust	-	5.00	0.30	77.70	16.90	50.30	6.70	0.20	42.70	DeSisto *et al*. (2010), Wei *et al*.2006
6	Sprucewoodchips	10.90	-	31.00	-	-	74.80	0.14	0.15	4.20	Saarnio *et al*. (2013)
7	Corn stovers	-	2.3	58.00	12.70	28.70	33.20	1.40	0.81	8.60	Lee *et al*. (2010)
8	Coconutshell	9.18	4.40	0.70	80.20	22.00	50.20	5.70	-	43.40	Raveendran *et al*. (1995), Werther *et al*. (2000), Shenbagavalli and Mahimairaja (2012)
9	Peanut shell	9.50	1.90	7.80	8.10	82.20	93.61	1.99	1.05	3.35	Apaydin-Varol *et al*. (2012)
10	Pine cone	9.80	1.20	4.70	6.70	87.40	95.16	2.63	1.61	0.60	Apaydin-Varol *et al*. (2012)
11	Peanut hull	8.60	-	9.30	18.10	-	81.80	2.90	2.70	3.30	Novak *et al*. (2009)
12	Switch grass	8.00	-	7.80	13.40	-	84.40	2.40	1.07	4.30	Novak *et al*. (2009)
13	Pongamiaglabrade oiled cake	11.20	4.30	11.60	14.60	69.50	75.00	3.26	5.00	12.58	Chutia *et al*. (2014)
14	Jute dust	-	9.44	10.78	15.07	64.71	70.25	2.78	4.04	22.93	Choudhury *et al*. (2014)
15	Sugarcanebagasse	9.30	1.30	8.57	9.17	80.97	85.59	2.82	1.11	10.48	Lee *et al*. (2013)
16	Coco peat	10.30	2.55	15.90	14.30	67.25	84.44	2.88	1.02	11.67	Lee *et al*. (2013)
17	Palm kernelshell (PKS)	6.90	-	6.86	12.29	80.85	87.85	2.91	1.11	8.14	Lee *et al*. (2013)
18	Cotton seedhull	8.50	6.53	7.90	18.60	67.00	87.50	2.85	1.50	7.60	Uchimiya *et al*. (2011)
19	Soybeancake	-	1.50	16.80	10.10	71.60	83.95	1.48	8.32	6.25	Apaydýn-Varol *et al*. (2012)
20	Sesame	-	3.40	36.80	22.00	37.80	86.64	3.10	6.93	3.09	Volli *et al*. (2012)
21	Neem	-	3.70	24.50	32.00	39.80	82.34	7.89	5.76	3.57	Volli*et al*. 2012

Table 5 continued...

Table 5 continued...

22	Mustard	-	4.80	28.10	21.00	46.10	85.43	4.79	6.17	3.41	Volli *et al.* (2012)
23	Shorearobusta seed	-	-	19.70	26.90	53.40	72.58	13.63	4.38	7.74	Singh *et al.* (2014)
24	Shreddedcotton stalk	-	-	-	-	-	79.30	1.12	1.53	16.83	Makavana *et al.* (2020)
25	Rice husk	9.42	-	-	-	-	28.44	1.0	0.31	7.62	YuehuiJia *et al.* (2018)
26	Cottonstraw (CS)	10.42	-	-	-	-	77.13	2.13	1.03	16.39	YuehuiJia *et al.* (2018)
27	Black locust	-	-	-	80.94	-	50.73	5.71	0.57	41.93	Kurt A Spokas (2010)
28	Douglas fir	-	-	-	81.50	-	52.30	6.30	0.10	40.50	
29	White fir	-	-	-	83.17	-	49.00	5.98	0.05	44.75	
30	White oak	-	-	-	81.28	-	49.48	5.38	0.35	43.13	
31	Ponderosa pine	-	-	-	82.54	-	49.25	5.99	0.06	44.36	
32	Peach pits	-	-	-	79.12	-	53.00	5.90	0.32	39.14	Kurt A Spokas (2010)
33	Walnut shells	-	-	-	78.28	-	49.98	5.71	0.21	43.35	
34	Corncobs	-	-	-	80.10	-	46.58	5.87	0.47	45.46	
35	Wheat straw	-	-	-	71.30	-	43.20	5.00	0.61	39.40	
36	Cotton stalk	-	-	-	70.89	-	43.64	5.81	-	43.87	
37	Corn stover	-	-	-	75.17	-	43.65	5.56	0.61	43.31	
38	Sugarcane bagasse	-	-	-	73.78	-	44.80	5.35	0.38	39.55	
39	Rice hulls	-	-	-	63.60	-	38.30	4.36	0.83	35.45	
40	Pine needles	-	-	-	72.38	-	48.21	6.57	-	43.72	
41	Cotton gin trash	-	-	-	67.30	-	39.59	5.26	2.09	36.38	
42	Wood	-	20	0.4-1	82	17	51.6	6.3	0.1	41.5	Chowdhury *et al.* (2017)
43	Bituminous coal	-	11	8-11	35	45					
44	Hybrid polar	-	45	0.5-2	-	-					
45	Switchgrass	-	13-15	4.5-5.8	-	-	44.77	5.79	0.31	49.13	
46	Miscanthus	-	11.5	1.5-4.5	66.8	15.9					
47	Sugarcane baggage	-	-	3.2-5.5	-	-					
48	Barley straw	-	30	6.0	46	18	45.7	6.1	0.4	38.3	
49	Wheat straw	-	16	4.0	59	21	48.5	5.5	0.3	3.9	

Table 5 continued...

Table 5 continued...

S. no.	Feedstock	pH	Moisture (%)	Ash (%)	VM (%)	FC (%)	C (%)	H (%)	N (%)	O (%)	Reference
50	Danish pine	-	8.0	1.6	71.6	19					
51	Rice straw	-	-	64.3	79	10.7					
52	Fire wood	-	7.74	1.98	80.86	17.16					
53	Grateloupiafilicina	-	4.93	22.37	55.93	17.01					
54	Birch	-	18.9	0.004	-	20	44	6.9	0.1	49	
55	Pine	-	17	0.03	-	16	45.7	7.0	0.1	47	
56	Polar	-	16.8	0.007	-	-	48.1	5.30	0.14	46.10	
57	Scots	-	-	-	-	-	56.4	6.30	0.1	-	
58	Willow	-	-	-	-	-	47.78	5.90	0.31	46.10	
59	Reed canary grass	-	-	-	-	-	45.36	5.81	0.34	48.49	
60	Dactylislomarata	-	-	-	-	-	42.96	5.70	1.90	49.44	
61	Festucaarundinacea	-	-	-	-	-	42.22	5.64	1.50	50.65	
62	Loliumperenne	-	-	-	-	-	43.12	5.80	1.28	49.80	
63	Olive baggage	-	-	-	-	-	66.9	9.2	-	21.9	
64	coconut shell	-	3.65	2.77	44.77	48.81	73.92	5.6	13.98	3.0	Priya *et al*. (2020)
65	pigeon pea wood	-	9.89	12.3	65.9	21.8	41.1	6.17	0.86	51.9	Tanquilut *et al*. (2019)
66	Soybean	-	-	6.58	76.96	16.46	-	-	-	-	Khardiwar *et al*. (2013)
67	Pigeon pea	-	-	7.05	77.07	15.88	-	-	-	-	
68	Mix biomass	-	-	7.34	79.14	13.52	-	-	-	-	
69	Prosopisjuliflora	-	-	1.7	83.05	15.94	-	-	-	-	
70	Leucaenaleucocephala	-	-	1.47	82.17	16.94	-	-	-	-	
71	Almond shells	-	-	-	-	-	47.9	6.3	0.32	44.27	Barisano *et al*., (2021)

VM = volatile matter, FC = fixed carbon (moisture, ash, volatile matter and fixed carbon in % and CHNO in wt. %).

respectively (Makavana *et al.*, 2020b). A total number of sixteen experiments were performed on the pyrolysis of shredded cotton stalk at four levels of temperature 200±15, 300±15,400±15 and 500 ±15 °C and four residence times of 60, 120, 180 and 240 min respectively (Makavana *et al.,* 2022).

Conclusion

This review focused on identifying mechanisms, chemical interactions and potential benefits of bio-char characteristics**.** Reading through the literature revealed that there are still certain issues that need to be resolved in order to convert biomass into products with value added, such as figuring out how different feedstocks or starting precursors affect how the pyrolysis process functions as a whole. Upgrading the pyrolysis reactions' consistency in terms of full energy and material partnerships so that they are sustainable for commercial uses. Bio-char has environmental advantages as well, including the reduction of greenhouse gas emissions, the cleaning up of contaminated soil and the sequestration of carbon. As a result, the creation and use of bio-char can be seen as a potential remedy for a number of contemporary issues.

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Author contributions

JM: conceptualization, formal analysis, investigation, visualization, writing original draft. PM: methodology, formal analysis, visualization. Conceptualization, methodology, writing—review and editing. DV: supervision, writing—review and editing TD: methodology, resources.

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Declaration

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Conflict of interest

The authors have no relevant financial or non-financial interests to disclose.

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