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Pyrolysis kinetics and potential utilization analysis of cereal biomass by-products; an experimental analysis for cleaner energy productions in India

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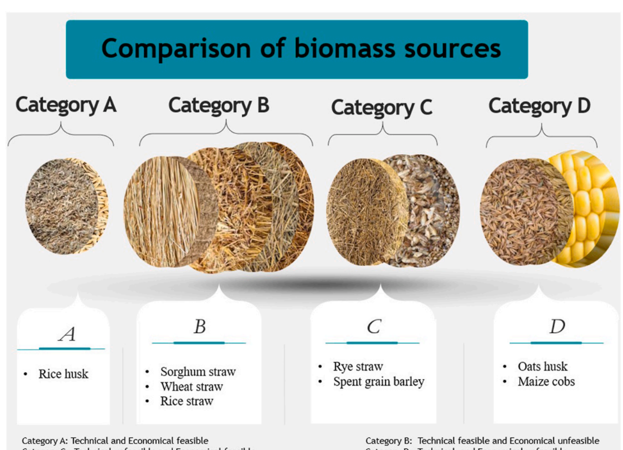
HIGHLIGHTS

- Barley, wheat, millet, oat, rice, rye straw, sorghum straw and maize cob are studied.
- The cereal wastes are compared based on some specifications.
- Wheat straws can cut emissions by 2%.
- 156 MMTPY of India's total emissions, could be eliminated by rice husk alone.
- Processing these nine feedstocks results in the production of 40 GW of electrical.

GRAPHICAL ABSTRACT



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ABSTRACT

The optimal utilization of biomass relies heavily on the specific material and individual needs. Cereal biomass by-products can potentially be employed in thermochemical processes such as pyrolysis and gasification. To compare biomass sources, ultimate analysis, biochar potential, proximate analysis, thermal gravimetric analysis, price per megajoule generated heat, surface texture, and availability are used. A global survey of biomass wastes and opportunities for heat generation is presented in the current article. Here, nine different cereal-based agricultural waste products (barley, wheat, millet, oats, rice, rye straw, sorghum straw/stalk, and maize cob) are studied. Cereal wastes are compared based on calorific value, water content, volatile matter, ash content and ash chemical composition, bulk density, charring properties, availability, and transportation. According to the estimate, 156 million metric tonnes per year, or 6% of India's total emissions, could be eliminated by rice husk alone. Wheat straws, on the other hand, can cut emissions by 2%. Additionally, processing these nine feedstocks

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might result in the production of 40 GW of electrical energy, which would increase the installed capacity of India's national electric grid by 9%.

1. Introduction

In the last few decades, one has observed a gradual shift from fossil fuels to renewable energy sources (Amjith and Bavanish, 2022). Solar, geothermal, and wind have rapidly been gaining popularity as sources of green energy and from a technology standpoint, they have attained allowable puberty (Khosravi et al., 2023; Behzadi et al., 2021). However, the high set-up cost of the systems and the irregular alternation of their power output still remain challenges for upscaling and widespread use (Paladin et al., 2021). CO_2 emissions in India were 34.81 billion metric tonnes in 2020 (declined 5% as a result of the COVID-19 epidemic). India has wholeheartedly dedicated itself to reaching carbon neutrality by 2070 (Ozgur et al., 2022). This net zero carbon emission aim can be attained in large part via carbon negative pyrolysis of residual feedstock (Brassard et al., 2021).

Biomass, which has already grown to be the 4th largest source of renewable energy among all countries, is widely available in most countries (Shokravi et al., 2021). It is highly versatile and is utilized for energy production, thermal energy, gas or liquid fuels, and fits as a raw material for chemicals (Hara Chakravarty et al., 2022). Compared to other sources of renewable energy like solar, biomass is a carbon-neutral source capable of being safely regulated without the need for power storage (Sobek and Werle, 2021). In addition, the revenues generated from the yield produced by biomass could also act as a great way to promote rural development and enhance agricultural production, especially in developing nations (Sadi and Arabkoohsar, 2020). For example, just in India, more than 135 million metric tonnes of cereals were produced in 2018 (Kayatz et al., 2019). According to the Indian ministry of agriculture, the production of major cereals like rice, maize, and bajra stood at 104.3, 21.8, and 8.1 million tonnes, respectively, in 2020 (Ladha et al., 2020). This means crop residues like straws of paddy, sorghum, millet, wheat, pulses, oilseed crops, maize stalks and cobs, cotton stalks, jute sticks, sugarcane trash, and mustard stalks are also produced in large quantities (Teigiserova et al., 2021). At the moment, out of this, a major portion of the crop residues (estimated at around 44.5 MT rice straws and 24.5 MT wheat straws) are burnt every year (Makavana et al., 2018). This leads to a massive amount of air pollution. One also sees the air quality deteriorating significantly during the harvest season, and the practice creates great harm to the soil, both in terms of nutrients and micronutrients (Zhao et al., 2017).

Another major problem related to the application of crop residue as fuel is the delocalized distribution and little energy amount (Meng et al., 2022). The suggested approach is to make biomass denser and change to bio-oil. Several pyrolysis companies followed this approach (Albashabsheh and Heier Stamm, 2021). In Canada, one could see companies like Envergent (www.envergenttech.com) following a solution of delocalized pyrolysis based on Ensyn's Rapid Thermal Processing Technology. Dynamotive, a company popular in fast pyrolysis and has cooperation with IFP, is following the hydrotreating of bio-oil. Karlsruhe Institute of Technology Bioliq produces fully synthetic diesel or gasoline from straw and other agricultural and forestal residues (Eberhard et al., 2020). Based on the fundamental macro thermogravimetric analysis (macro-TGA), a wide range of these pyrolysis processes in various machines would be predicted (Onsree et al., 2018). Recent research has looked into macro-TGA as a small-scale pyrolysis approach for studying biomass thermochemistry and developing a procedure that is tailored to the feedstock (Zabaniotou et al., 2015).

Biomass is also used in a variety of technologies and applications rather than as a fuel. For example, biogas generation from anaerobic digestion of biomass is a technique that has been used widely and successfully in rural India (Agarwal et al., 2022). This technique works particularly well for wet feedstock which is unsuitable for applications like pyrolysis (Arelli et al., 2022). Additionally, organic materials such as crop residues are composted and used as organic amendments for improving soil productivity and health. Residues like oats husk, sorghum, etc. are used as animal feed (Godoy et al., 2018). In the construction industry, natural fibers derived from biomass augmented by polymer concrete base composites have been gaining consideration since these fibers are cheap, lightweight, simple to process, sustainable, and have a high specific modulus (Saba et al., 2015).

Based on the literature already mentioned, pyrolysis of leftover feedstock can significantly reduce emissions. Further, a variety of activities are being conducted to demonstrate and advance this technology. Despite this, no comprehensive analysis has been conducted of the total amount of carbon removed from processed agricultural residues. Additionally, feedstock classification is lacking, considering pyrolysis as a carbon removal technique. In light of this, different biomass types shouldn't simply be used for fuel production. It would be better to focus on finding the best applications for each type of agricultural residue. To create high-value applications for feedstocks, different industries must experiment with a variety of types. In addition, this will solve the fundamental problem of surplus biomass getting burned and causing air and soil pollution. However, it will also help many industries function in a more sustainable manner. The present research aims to address this gap by investigating worldwide access to biomass wastes. It also assesses the application capacity for heat generation for nine different most commonly grown cereal-based agricultural waste products. Cereal wastes are compared based on caloric value, ash content, water content, volatile matter, ash chemical composition, bulk density, charring properties, availability, and transportation.

2. Materials and methods

2.1. Sampling and objective

To give a deeper conception of the different thermochemical processes, their underlying chemistry, and their effect on different biomass types, Macro-TGA analysis is conducted in the laboratory on a variety of biomass samples. This provides information on the determination of endotherms, exotherms, weight loss on heating, cooling, etc. Based on the findings, effective parameters are determined, and the net achievable output for electrical and heat energy, as well as carbon emissions, from an effective thermochemical process, is computed. The test setup used for this purpose has been illustrated in Fig. 1. For our experiments, 9 various cereal-based agricultural waste products (wheat straw, rice husk, maize cobs, barley spent, millet husk, oats hull, rye straw, and sorghum straw) from parts of Rajasthan, Madhya Pradesh, Gujarat, and Punjab are studied.

2.2. Experimental setup

In our test setup, a crucible is placed over the weight balance supported by a 25 cm long rod. This setup accommodates up to 40 g of sample specimen weight which is larger than the other standard available equipment. Experimenting with large sample sizes provides readings of substantial weight loss. Before the experiment, we allowed 24 h for the biomass to dry at 104 °C. Then the prepared sample is put in a surrounding vessel (100 × 100 × 225 cm) in the pyro-oven. Then the temperature lets it get higher. To provide the inert ambient during the experiment, 0.5 l/min N2 blows through the surrounded vessel. Temperatures are evaluated in the middle of the biomass samples placed inside the metal container. An electronic balance constantly stores the

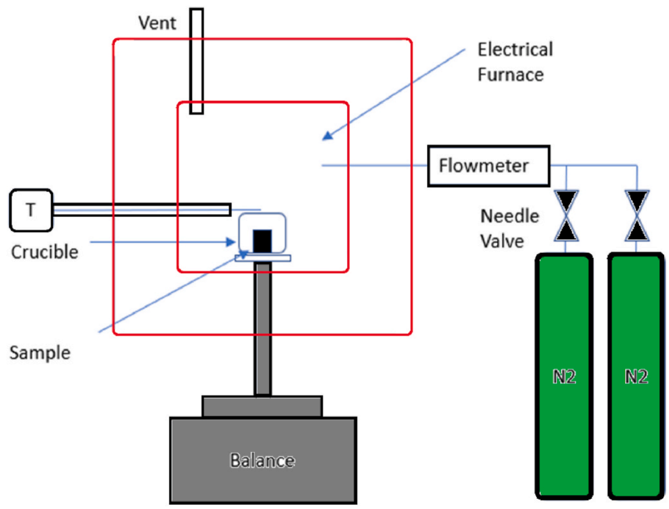

Fig. 1. Schematic diagram of Macro-TGA analysis using Pyro Oven 100.100.225 cm, 1.5 kW.

loss of mass data during the experiment.

2.3. Methodology

For this experiment, the study conducted Macro TGA on 9 types of biomasses to analyze which types are the most suitable for our use. To do so, the study used the following methodology to evaluate every feedstock including pre-TGA measurements, macro-TGA, and post-TGA measurements.

Pre-TGA measurements (properties of feedstock): for a feedstock, the study measures the following before conducting TGA on the sample: (1) LHV (lower heating value) and HHV (higher heating value) of the feedstock; (2) proximate analysis: water, ash, and volatile content and fixed carbon; (3) ultimate analysis of the feedstock (% of Carbon, Hydrogen, Oxygen, and Nitrogen) (Skreiberg et al., 2011).

Macro-TGA: we use 20–25 g of each sample for this process and the thermal degradation kinetics of a biomass sample is measured. Thermograms are plotted for each sample depicting a scheme of residual weight as a percentage of primary weight versus temperature. These data are analyzed to specify the primary degradation temperature, the rate of thermal degradation in active and passive pyrolysis zones, and the residual weight at 700 °C (Perkins et al., 2018).

Post-TGA measurements (properties of biochar): the residual weight at 700 °C is the biochar which is further analyzed to measure the following properties (1) LHV and (2) ultimate analysis of the biochar (% of Carbon, Hydrogen, Oxygen, and Nitrogen) (Miao et al., 2021).

Using the parameters that are measured for feedstock and biochar, one can calculate the following for energy and elemental composition of volatile (pyrogas). Based on the LHV of the feedstock and the LHV of the biochar, the lower heating value of the pyrogas is determined by measuring the net energy difference between the input biomass and the resulting biochar (Papari et al., 2019). Similarly, the difference between the input feedstock and the residue biochar is used to calculate the elemental analysis of the pyrogas. Thereby the net proximate analysis of the pyrogas is produced (including Carbon, Hydrogen, Oxygen, and Nitrogen). According to studies, when pyrogas are employed in a gas generator, the syngas to electricity conversion ratio is found to be as high as 39.4%. The technique generates an electric energy equivalent to 39.4% of the pyrogas LHV. At 350 °C, the residual heat energy was utilized for various purposes such as district heating and/or district cooling (Gobbato et al., 2015). Carbon captured may be determined using the carbon content of biochar (measured through the ultimate analysis of biochar). Based on the feedstock's availability, the total energy output and carbon capture potential of each feedstock may be determined (in Million Tonnes per Year). This information may also be used to compute the amount of electricity produced and the number of machines necessary to do so. After that, it was compared to overall carbon emissions and the percentage decrease in carbon emissions that the pyrolysis machine could accomplish.

3. Results and discussion

3.1. Observations and TGA results

Before performing TGA on a feedstock, we perform proximate analysis, and ultimate analysis and measure the LHV and HHV of the feedstock. The results for the same have been listed in Tables 1–3. Ten grams of the arrived sample was used in each case to measure the lower heating value of feed in the bomb calorimeter. The sample was heated to 120 °C for 6 h and then and 10-g sample was picked again to measure the higher heating value of the sample. The values of LHV and HHV are listed in Table 1. The net loss in solid (wt%) on heating to 120 °C for 6 h provides the moisture content in the feedstock. Subsequently, the biomass was heated to 900 °C in the furnace with a flow of air. The mass remaining in the solid was used to calculate the ash (wt%). While the fixed carbon was calculated by removing the ash content from the solid (wt%) remaining at 700 °C (at the end of the TGA experiments). The remaining mass proportion was calculated as the volatile segment. The proximate analysis values (moisture, ash, volatile and fixed carbon) are listed in Table 2.

Here we present a discussion about each cereal biomass by-product separately including specifications, properties, thermal degradation, challenges of utilization, uses, availability and price. Figs. 2 and 3 represents thermogravimetric analysis and derivative thermogravimetric analysis of 9 feedstocks at 10 °C/min with N_2 purge at 5 l/min. Then, Fig. 4 represents the thermogravimetric analysis and derivative thermogravimetric analysis of 9 feedstocks at 10 °C/min with N_2 purge at 5 l/min for each feedstock separately. Afterward, a discussion is carried out for each feedstock individually.

3.1.1. Rice husk

Rice husk is a porous, brown material with high moisture absorption capacity. It has a density of 83–125 kg/m^3 and can absorb moisture ranging from 5% to 16% of its weight. Rice husk undergoes gradual weight loss due to moisture release and rapid pyrolytic degradation between 233 °C and 340 °C. To recover most volatiles, the biomass should be processed to 620 °C (Gebretatios et al., 2023). Transporting rice husk is expensive due to its low density (Mohd Yahya et al., 2021). It can be transformed into briquettes or pellets, but this is a costly and energy-intensive process. However, rice husk is valued as an alternative fuel for drying and is widely used as boiler fuel in India. Its potential for energy generation and biomass-to-energy projects is significant, with a

Table 1
LHV and HHV of different Feedstocks.

Biomass	LHV	HHV	Moisture	Ash	Volatile Content	Fixed Carbon
	(MJ/kg)		(wt%)			
Rice Husk	12.84	14.09	10.1	14.2	52.3	23.4
Wheat Straw	13.96	15.4	12.9	6.1	63.02	17.98
Rice Straw	12.65	13.89	7.93	19.19	54.68	18.2
Maize Cobs	17.34	19.3	13.1	3.5	67	16.4
Barley- Spent Grain	16.9	18.23	8.6	9.56	69.59	12.25
Millet Husk (dry))	16.08	17.4	9	22.1	59.67	9.23
Oats Hull	16.46	18.9	10.1	3.2	69.6	17.1
Rye Straw	14.92	16.26	13.5	3.95	65.3	17.25
Sorghum Straw	17.6	19.1	7.72	7.13	65.38	19.77

Table 2
Ultimate analysis of different feedstocks.

Biomass	Carbon (wt %)	Hydrogen (wt %)	Oxygen (wt %)	Nitrogen (wt %)
Rice Husk	34.99	4.58	34.18	1.95
Wheat Straw	42.45	5.27	32.76	0.52
Rice Straw	38.24	5.2	28.57	0.87
Maize Cobs	50.2	5.9	43.5	0.42
Barley- Spent Grain	43.59	6.18	37.22	3.46
Millet Husk (dewatered)	42.77	5.28	19.76	1.09
Oats Hull	46	5.91	33.39	1.4
Rye Straw	41.08	4.58	36.49	0.4
Sorghum Straw	40	5.2	40.7	1.4

price of 2–3 INR per kg, approximately 0.21 INR or 0.0028 USD per MJ of energy (Mohanty et al., 2017).

3.1.2. Wheat straw

Wheat straw has a bulk density ranging from 97.52 to 177.23 kg/m3 and a moisture content of 5.02–7.79 wt%. The average particle size falls within the range of 0.38–0.69 mm. Each kilogram of wheat grain yields around 1 kg of straw (Das, 2022). Wheat straw can be converted into various products, including fertilizer, pulp, paper, nano-materials, and bioethanol. It offers a renewable and abundantly available resource for these applications, with a price of $0.062 per kg ($0.0037 per MJ of energy) (Yusup and Rashidi, 2021).

3.1.3. Rice straw

Rice straw is the by-product of rice harvesting. It has a moisture content between 6.58 and 6.92% and particle sizes ranging from 0 to 0.710 mm (Kaur and Singh, 2022). The bulk density of rice straw is lower than that of rice husk. Rice straw has ash content of around 18.67–29.1%, which reduces its calorific value and can cause problems in energy conversion. The alkali, potassium, and silica content in the ash can lead to fouling, corrosion, and erosion in equipment. Rice straw is of low quality for animal feed but can be used as a potential feed additive. It is priced at $0.033 per kg, approximately $0.0037 per MJ of energy (Skreiberg et al., 2011).

3.1.4. Maize cobs

Maize cobs are produced during the corn processing. They consist of three segments: pith, woody ring, and chaff (Riley and Marsh, 2021). The degradation of corn cobs occurs in four segments, with significant weight loss observed between 250 °C and 500 °C. Maize cobs can be utilized in the generation of activated carbons and as a source of energy. The price of maize cobs is $0.069 per kg, approximately $0.0036 per MJ of energy (Pickl, 2019).

3.1.5. Barley spent grain

Barley spent grain is a by-product of brewing production. It is rich in protein, fiber, minerals, and lipids, making it suitable as animal feed. It can also be used as a source of dietary fiber and for milk generation in cattle. Barley spent grain undergoes mass loss due to moisture removal and pyrolysis of the lignocellulosic media. It can be used for energy generation through drying and combustion or biogas production by anaerobic digestion (Pickl, 2019).

3.1.6. Millet husk

Pearl millet (Pennisetum glaucum) is a tall grass grown in drought

Table 3
LHV and Ultimate Analysis of biochar.

Biomass	Carbon (wt%)	Hydrogen (wt%)	Oxygen (wt%)	Nitrogen (wt%)	LHV (MJ/kg of feedstock)
Rice Husk	52.89	2.80	6.24	0.28	15.38
Wheat Straw	65.70	4.44	4.36	0.14	15.76
Rice Straw	42.34	2.23	3.98	0.10	11.84
Maize Cobs	66.75	3.64	11.55	0.46	15.27
Barley- Spent Grain	46.61	3.01	6.33	0.20	12.89
Millet Husk (dewatered)	24.15	1.29	3.91	0.08	7.59
Oats Hull	69.91	3.63	10.24	0.44	22.04
Rye Straw	65.90	4.75	10.52	0.17	17.14
Sorghum Straw	58.79	4.21	10.18	0.30	13.1

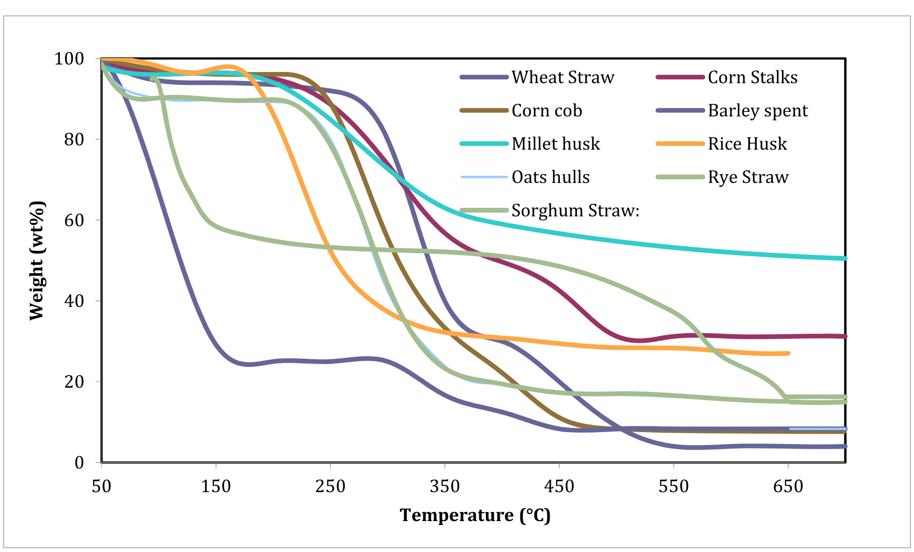

Fig. 2. Thermogravimetric analysis of 9 feedstocks at 10 °C/min with N_2 purge at 5 l/min.

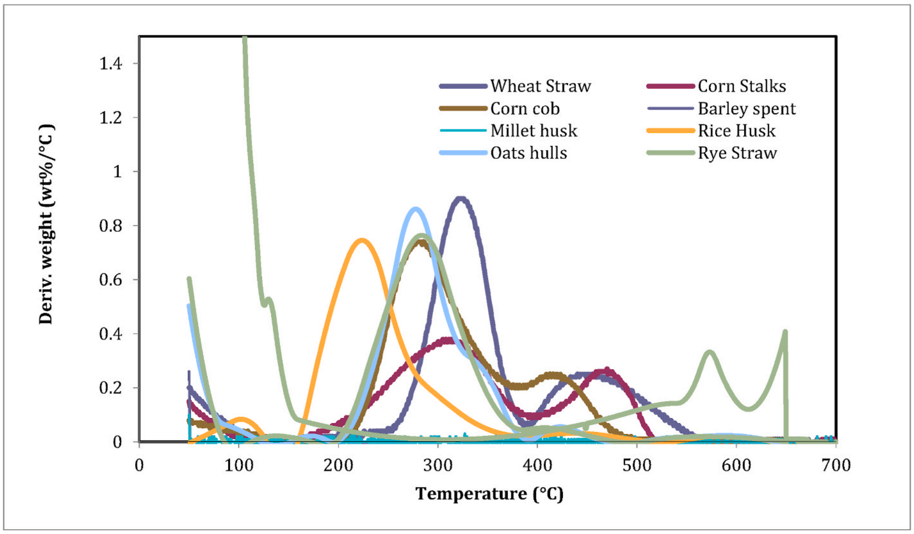

Fig. 3. Derivative thermogravimetric analysis of 9 feedstocks at 10 °C/min with N_2 purge at 5 l/min.

areas with low soil fertility and warm dry climates. It is widely cultivated in India, Africa, and the US for grain production, grazing, and hay. The production of pearl millet is highest in the state of Rajasthan, India. It has potential for bioethanol production and paper manufacturing due to its cellulose-rich content. The recommended pyrolysis temperature for millet husk is lower than that of rice husk and wheat husk (Agarwal et al., 2022).

3.1.7. Oats hull

Oat hulls are the outer shell coating of oat cereal grain. They are available in large quantities at oat milling machines and consist of around 30% of the grain. Oat hulls have a low density and are burned in boiler systems for power generation. The remaining char can be used in farm fields. Oat hulls have potential uses in animal feed and bioethanol production. The price of oat hulls is 0.16 INR per MJ of energy (Riley and Marsh, 2021).

3.1.8. Rye straw

Rye straw is known for its waxy bright finish and long length. It is used as bedding material and has a production rate of two to three tonnes per acre. Rye straw undergoes thermal degradation between 300 and 360 °C, making it suitable for pyrolysis. However, the formation of ergot in rye straw can make it poisonous and a challenge for animal feed. Rye straw is also used as a cover crop and can be composted. The price of rye straw is 0.62 INR per MJ of energy (Mohanty et al., 2017).

3.1.9. Sorghum straw

Sorghum straw is composed of the leaves and stems of the sorghum plant. It has a high production yield and a short growth period. Sorghum straw undergoes decomposition between 290 and 415 °C, mainly involving hemicellulose and cellulose molecules. It has a high volatile content and low lignin content, making it suitable for pyrolysis. Sorghum straw can be used as a feedstock for direct combustion, as a replacement for coal in power plants, and in various industrial applications. It also has potential for bioethanol production, paper manufacturing, and as a building material. The price of sorghum straw is 0.16 INR per MJ of energy (Mohanty et al., 2017).

3.2. Calculations based on TGA experiment

Using the biochar and feedstock data (Tables 1 and 2) provided above, the calorific value and elemental composition of the pyrogas were computed for each feedstock. Based on Table 4, one would compute the electric energy produced by the pyrogas process based on research that reveals the heat-to-electricity conversion ratio in biomass gasification systems is 39.4%. The rest of the energy remains as thermal energy for many processes such as district heating and cooling. The calorific values and elemental composition of all feedstocks were calculated using the technique outlined above. Table 3 represents LHV and ultimate analysis of pyrogas. Hydrogen, Nitrogen, Oxygen, and Carbon percent by weight (of the original feed) for all feedstocks were determined in the same way. The values calculated for the same have been listed in Tables 3 and 4 Herein we find that the LHV of Rice Husk and Maize cobs has the lowest and highest amount of energy respectively. The low C/O ratio of Rice Husk and Rice Straw lead to the low LHV (7.06 and 8.22 MJ/kg of feedstock respectively) for the respective pyrogas. While other feedstocks had 10–14.3 MJ/kg, attributing to % and H/C ratios.

The energy content in pyrogas can be utilized to produce electricity and heat energy was estimated in Table 4. Typical modular efficiency pyrolysis plants operated by various organizations have an operating capacity of 2 tonnes per day (TPD) to 10 tonnes per day. And therefore, based on the total production of various feedstock the total potential energy production per pyrolysis operation plant was estimated for an operational machine 2 tonnes per day, of feedstock on a dry basis. It shows 2 TPD maize cobs and sorghum straw can produce up to 129.1 and 127.08 kWe. With distributed feedstock in rural areas, this electricity can both support local production or various commodities and be transferred to the grid. In addition, there is heat energy (99.65–201.94 kWth) produced from the gas generator at 350–400 °C. Some of this feedstock can be used for the drying of wet feedstock, nevertheless finding local usage for the remaining heat might be challenging since energy in form of heat cannot be stored or transmitted for long distances.

2–10 tonnes of biomass are processed in a typical pyrolysis small-scale operation. So, using the obtained electric and thermal output, we calculated the total electric and heat energy that a pyrolysis plant produced for the given feedstock. In addition, the capacity of a typical plant to collect carbon from the feedstock was determined using the feed rate of the machines as described in the literature. The normal output of a 2-ton-per-day machine would be 60–130 kWe. Maize Cobs were discovered to have the maximum electrical production for certain equipment (129.1 kWe). While, according to the calculations, a typical reactor consuming 10 tonnes of feedstock per day would produce 0.5–0.8 MW of power. In addition, 1 MW of residual heat at 350 °C is available for other purposes. These common pyrolysis facilities may also sequester 500–2000 tonnes of carbon each year.

Table 5 shows the total Energy production and Carbon Capture Potential of each Feedstock which can be calculated based on the

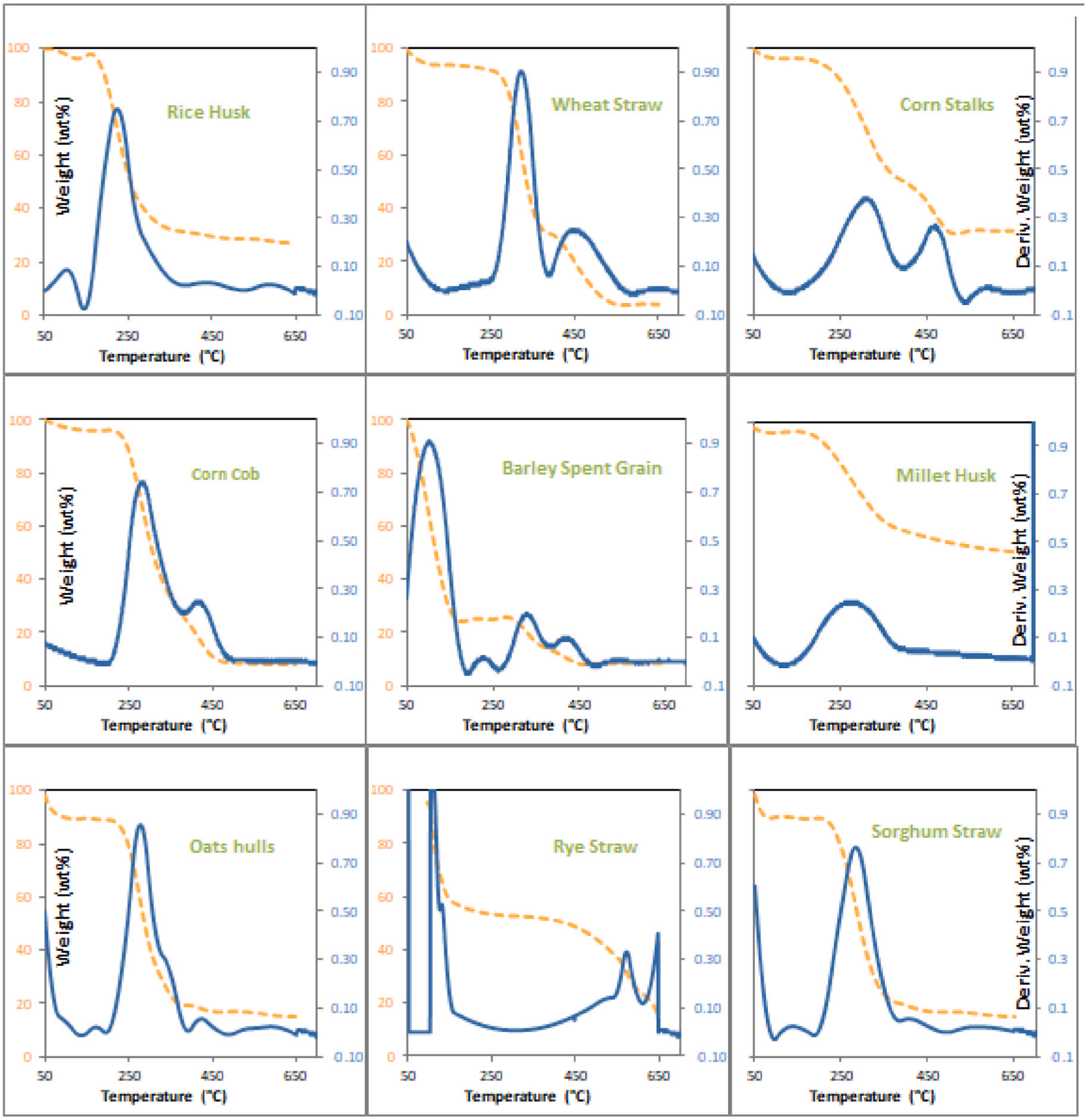

Fig. 4. Thermogravimetric analysis and derivative thermogravimetric analysis of 9 feedstocks.

Table 4
Estimated electricity production, heat production, and Carbon capture per kg of feedstock.

Biomass	Electricity (kWe)		Heat Energy (kWth)		Total Carbon Capture	
	Per kg Fed	2 TPD	Per kg Fed	2 TPD	CO2/kg fed	2 TPD
	kWe/kg fed	kWe	kWth	kWth	kg	Ton/yr
Rice Husk	0.76	63.71	1.20	99.65	0.73	532
Wheat Straw	1.10	91.77	1.72	143.55	0.58	423
Rice Straw	0.89	74.24	1.39	116.11	0.58	424
Maize Cobs	1.55	129.11	2.42	201.94	0.49	356
Barley- Spent Grain	1.53	127.19	2.39	198.94	0.37	272
Millet Husk*	1.48	123.70	2.32	193.48	0.28	203
Oats Hull	1.30	108.21	2.03	169.25	0.52	380
Rye Straw	1.22	101.89	1.91	159.73	0.51	374
Sorghum Straw	1.52	127.08	2.39	198.76	0.58	423

availability of the feedstock (in Million Tonnes per Year). This data was also used to calculate the Electricity generated and the number of machines required to achieve the same. India produces 500 MT of crop residue annually, according to a mean estimate. Despite being used primarily for fodder, raw material for power generation, etc, there is yet

Table 5
Total energy and Carbon capture potential.

Biomass	Production	Total Machines Needed		Electricity	Carbon Capture
	MTPY	2 TPD	10 TPD	GWe	MTPY
Rice Husk	214	2,93,151	58,630	18.7	156.0
Wheat Straw	103	1,41,096	28,219	12.9	59.7
Rice Straw	32	43,836	8767	3.3	18.6
Maize Cobs	18	24,658	4932	3.2	8.8
Millet Husk (dewatered)	19	26,027	5205	3.2	5.3
Oats Hull	4.49	6151	1230	0.7	2.3

a massive excess of 140 MT out of which 92 MT is annually burnt, significantly in the northern states such as Punjab, Haryana, and Uttar Pradesh. Farmers with the need for fodder must get the stubble removed by hand or utilize further expensive special machines to perform this duty. To harvest each 0.4 ha of the wheat crop, to hire a combine harvester, one should pay $11. After harvest, the cost of getting the stubble picked up is $48/ha. So, the worthiness of fodder is discounted, and burning would be economic in the end to clean the farm. The extensive firing of crops rises CO_2, CO, N_2O, and NO_x in the atmosphere and causes a terrible increment in air pollution. One would notice a worrying decrease in the air quality in northern India to about double the permissible Indian standard and ten times more than the WHO standard during the harvest season. The table reveals that rice husk alone can offset 156 million metric tonnes per year or 6% of India's total emissions. Wheat straws, on the other hand, can lower emissions by 2%. The 9 feedstocks may catch a total of 250.7 million metric tonnes per year. As India produces 2.5 BMTPY of carbon emissions, this combination can result in a 10% decrease in carbon emissions. In addition, 40 GW of electrical energy can be generated from processing these 9 feedstocks (see Table 5). The national electric grid in India has an installed capacity of 393.389 GW as of 31 December 20, 2172. Renewable power plants, which also include large hydroelectric plants, constitute 37% of India's total installed capacity. The additional 41.9 GW can add another 10% increase in renewable energy production.

3.3. Comparison of cereal residues

Small-scale Pyrolysis and gasification can be argued to be very efficient energy conversion processes because they accept a wide variety of inputs and give multiple useful products which include: syngas, heat, power, bio-fuels, fertilizer, and biochar. The generation of electricity is the most basic application of pyrogas. This is apparent that the provided feedstock has a lot of waste processing and energy-generating possibilities. Syngas produced also have the potential for Methanol production which will be also explored on a large scale in the future. Biochar helps in soil amendment, and carbon sequestration and also controls methane gas emissions. Biochar also has great potential for energy applications due to its high energy content in it. All the major cereals studied in this paper are divided into 4 different categories which are as follows.

Category A: Currently suitable biomass for the pyrolytic system: Rice husk is generally used as a fuel for steam generation in rice mills. It is also used in gasifiers for electricity generation. A portion of the husk remains unutilized and is burned. The production of rice husk is about 28 million tonnes per year. Rice husk used in thermochemical machines captures 38.30 MT of CO2 per year. The material that remains after combustion, known as Rice Husk Ash, is high in silica content, provides good insulation, and has a large surface area for chemical reactions.

Category B: Has potential for pyrolysis systems in the future- Sorghum straw, Wheat straw & Rice straw. Sorghum Straw is used for industrial purposes such as in the production of potable alcohol, malt, beer, liquids, gruels, starch, and adhesives; as core binders for metal casting; in ore refining; and as grits as packaging material. Forage sorghums are used primarily as silage for livestock. They are sometimes grown and harvested with soybeans to improve the protein content of the silage. Sudangrasses and sorghum-sudangrass hybrids are grazed by livestock or fed as green chops or hay. Sorghum young plants produce hydrocyanic acid when hydrolyzed. Straws have the potential for energy generation in thermochemical systems. Annually, 14 MT of sorghum straws is produced in India which means annually 20.16 MT of CO_2 can be captured per year. Wheat straw and Rice straw have the potential for energy generation in the form of pallets in the thermochemical process. Currently, they are used as livestock feed and the rest is burned in the fields as cutting and transportation are costly for the farmers. 258 MT and 233 MT CO_2 can be captured from wheat straw and rice straw respectively per year. However, rice straw and husk have high ash content and high content of incombustible ash which can produce sandblasting effects in the reactor. Therefore, rice residues should be mixed with another biomass in proportions that might be challenging.

Category C: Low-quality biomass (moisture, calorific value, low-volatile fraction, limited availability) has no potential for utilization in a pyrolytic system- Spent grain barley and Rye straw. Spent Grain Barley is currently being used in the production of fermented beer. Spent grain has a moisture content of up to 70 %. Therefore, the drying cost and the transportation become uneconomical. Most of the spent grains are also utilized as cattle feed. Spent grains are microbiologically unstable so cannot be stored for a long period. Also, additional equipment will be required for dying up barley husk (70–80 % moisture) which is uneconomical. Rye straw is currently used in livestock bedding and crafts etc. Rye straw has potential for energy production as it has high energy content (17 MJ/kg). Rye straw pyrolytic systems can help capture 0.60 g/per g of carbon. One disadvantage of using rye straw is the cost of collection and transportation. Rye straw production in India is also very limited.

Category D: Other uses of biomass are of higher value and therefore do not make sense to be used for pyrolysis including- Oats husk, Maize cobs. Maize Cobs are being currently utilized in the production of large-surface area activated carbons for the removal of organic pollutants from drinking water. Cob corn is also one of the solid wastes which contain pentosan and has economic value to be produced as furfural products. Maize cobs do have the potential for use in energy production. However, producing activated carbon and furfural gives higher value output. Oats husk is currently being used for making furfural, high-fiber animal feed. It is important to palletize the feedstock for burning into the thermochemical reactors for process efficiency, economical transportation, and solving storage problems. Rice straw and husk have high ash content and high content of incombustible ash which produces sandblasting effects in the reactor. Therefore, rice residues should be mixed with another biomass in proportions that might be challenging. Oats and Barley are also unfeasible for energy applications as Oat and barley production in India is very limited.

4. Conclusion

Given its abundant availability in India, grain residue has the capacity to emerge as a significant source of fuel for pyrolysis machines. In this article, Macro TGA was used to examine the thermal degradation kinetics of nine of the most common biomass feedstocks. A feedstock screening technique was created based on:

- Logistical aspects such as availability, current value, other sectors where the feedstock is utilized, feedstock transportability, and so on
- Technical parameters such as moisture content, thermal degradation kinetics, and so on

Feedstocks tested were classified into 4 categories using a method of screening as follows:

(A) Currently suitable biomass for pyrolysis systems,
(B) Has future potential for pyrolysis systems,
(C) Low-quality biomass (moisture, calorific value, low-volatile fraction, limited availability)
(D) Biomass which has other uses of significant value.

Categories C and D have no potential for pyrolysis systems. The study shows that the total carbon capture achievable from the nine feedstocks evaluated is roughly 230 million tonnes per year. As a result, the successful application of pyrolysis technology to large agricultural leftovers might lower India's carbon emissions by 10% while increasing electricity output by another 10%–12% (41.9 GWe bioelectricity production). It was also computed how much carbon was captured by these methods. Because of the vast availability and abuse of feedstock in the current circumstances, this went a long way to proving that pyrolysis as a system has a lot of potential to create energy.

CRediT authorship contribution statement

Krishna Hara Chakravarty: Data collection, Draft manuscript preparation. **Meisam Sadi:** Draft manuscript preparation. **Harapriya Chakravarty:** Data collection, Analysis, Interpretation of results. **Jakob Andersen:** Interpretation of results. **Bobby Choudhury:** Interpretation of results. **Thomas James Howard:** Study conception and design. **Ahmad Arabkoohsar:** Study conception and design.

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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