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Pyrolysis of poultry manure with agricultural biomass for the production of biofuel – An experimental study on feedstock ratio for synergistic evaluation and product characterization

K. Sujit[1], M.Veeramanikandan[2], C. Sowmya Dhanalakshmi[3], P. Madhu[4]*, S. Ajit[5], T. Stephen Livingston[6], Amara S A L G Gopala Gupta[7] & J.Devaraj[4]

[1]Department of Electrical and Electronics Engineering, Amrita School of Engineering, Amrita Vishwa, Vidyapeetham, Bengaluru 560035, Karnataka, India

[2]Department of Mechanical Engineering, SRM Institute of Science and Technology, Ramapuram Campus, Chennai 600089, Tamil Nadu, India

[3]Department of Mechanical Engineering, SNS College of Technology, Coimbatore 641035, Tamil Nadu, India

[4]Department of Mechanical Engineering, Karpagam College of Engineering, Coimbatore 641032, Tamil Nadu, India

[5]Xavier Institute of Management & Entrepreneurship, Chennai 602105, Tamil Nadu, India

[6]Department of Mechanical Engineering, RVS Technical Campus Coimbatore, Coimbatore 641402, Tamil Nadu, India

[7]Department of Computer Science and Engineering, Koneru Lakshmaiah Education Foundation, Vaddeswaram 522302, Andhra Pradesh, India

*E-mail: pnpmadhu@gmail.com

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Co-pyrolysis is an efficient way of reducing environmental pollution and turning poultry manure into biofuels and chemicals. This study examines a novel approach to turning poultry manure (PM) into biofuels by pyrolyzing it with agricultural biomass. The impact of combining sugarcane bagasse (SB) with PM under different proportions and their effect on the yield of pyrolysis oil, char, and gas were evaluated by mixing SB with PM in different mass ratios. The blended feedstocks PM80SB20 (80% PM + 20% SB), PM60SB40 (60% PM + 40% SB), PM50SB50 (50% PM + 50% SB), PM40SB60 (40% PM + 60% SB), and PM20SB80 (20% PM + 80% SB) have been prepared and co-pyrolyzed along with the individual pyrolysis of PM and SB. According to the findings, the yields from PM pyrolysis were 45.01 wt% for oil, 39.52 wt% for biochar, and 18.83 wt% for the gas product. The quality of the oil, char, and gaseous products is significantly enhanced by co-pyrolyzing PM with SB. The highest production of oil components (64.8 wt%) with positive synergy is obtained with the lowest yield of oxygenated elements under the ideal experimental conditions of 40% SB loading. It is also found that the co-pyrolysis oil has a higher calorific value than the PM pyrolysis oil. These findings demonstrate that, in contrast to PM pyrolysis products, PM could be recycled through co-pyrolysis with SB to produce oil, char, and gas with better properties.

Keywords: Feedstock effect, Poultry manure, Sugarcane bagasse, Synergistic analysis, Yield analysis

Introduction

In order to address social, economic, and environmental issues and achieve the sustainable development goals, renewable energy is essential[1]. It reduces carbon emissions, promotes economic empowerment, and ensures universal access to clean energy, fostering a cleaner, more equitable future[2]. One of the most important ways to combat climate change and energy sustainability is to use renewable energy to produce fuel. This method produces sustainable fuels like hydrogen and green gasoline by combining cutting-edge fuel production technologies with a variety of renewable sources, including solar, wind, and biomass. Biomass serves as a key source for biofuel, which is considered one of the renewable fuels that are derived from organic materials, such as plants and agricultural residues. The conversion of biomass into useful energy products and materials encompasses a variety of techniques. These techniques can be generally categorized into thermochemical, biochemical, and physicochemical processes. Each technique has unique advantages and applications[3]. Pyrolysis, gasification, and torrefaction are considered effective thermochemical conversion techniques that convert biomass into biofuels and chemicals[4]. Enzymatic hydrolysis and anaerobic digestion come under biochemical conversion methods that convert organic matter into biogas. In physicochemical conversion both physical and chemical techniques are combined to improve biomass properties, leading to the production of value-added products.

Among various biomass conversion methods, pyrolysis is getting more attention due to its effective waste management and higher product yields. Pyrolysis turns organic materials into useful products like gaseous, liquid, and solid fuels[5]. The pyrolysis of silver grass, pine, and acacia harvested from heavy-metal-contaminated soil was assessed by Park *et al.* who found that the biomass type and the pyrolysis technique used had a substantial impact on the yields and properties of bio-oils and biochars[6]. In this study, the yields and properties of pyrolysis differ depending on the technique and kind of feedstock. The study recommended two-stage pyrolytic of biomass for producing high-quality char and chemicals. Similar to individual pyrolysis, the co-pyrolysis method is easy to use and efficient in producing high-quality pyrolysis oil[7]. Under different process parameters such as reactor temperature, feed size, and heating rate, Dhanalakshmi *et al.* examined the yield and chemical characterization of pyrolysis oil and char products from the co-pyrolysis of woody and grass-type biomass[8]. In this study, a maximum pyrolysis oil production of 47.10 wt% was achieved while it pyrolyzed at 500°C and 1.0 mm particle size. Co-pyrolysis of *Erythrinaindica* and *Azadirachtaindica* at different ratios improves physicochemical qualities and increases the yield of bio-oil (29.51-32.40% by weight). At a 1:1 ratio, the co-pyrolysis process reached a peak calorific value of 36.80 MJ/kg[9]. The produced char in this work had 79.23% of carbon, and the gas fractions included 7.45% H and 34.26% CO.

The poultry sector is world's biggest and fastest-growing livestock production sectors. The waste from chickens and other birds that can be used into fuel or fertilizer is called poultry manure (PM)[10]. Poultry waste is typically a blend of feed leftovers, feathers, excrement, and litter. To ensure a secure and healthy working environment for poultry farm employees, this waste needs to be disposed of in a safe manner[11]. Due to leaching degradation of soil and water bodies, existing disposal techniques, including land filling and biodigestion, are not recommended[12,13]. About 3430 million poultry live in India, the country generates 25 to 40 million tonnes of waste annually. This nutrient-rich waste represents both an environmental challenge and a valuable bioresource. In many states or regions, poultry production can account for a significant portion of the agricultural economy due to its regional nature. The waste can be used to enhance the quality of soil because it is rich in nutrients, including potassium, phosphorus, and nitrogen[14]. However, in most regions, improper handling and disposal practices lead to environmental issues such as odour emission, groundwater contamination, and greenhouse gas release. PM co-pyrolysis offers a viable method for producing biofuel by utilizing the thermochemical transformation of organic waste into useful energy sources. By working in combination with various feedstocks, this technique not only solves waste management issues but also improves the quality and yield of biofuel[15]. According to Parthasarathy *et al.* co-pyrolysis of poultry manure at 600°C produces the largest amount of pyrolysis oil (41%). When mixed with other manures, the ideal blending ratio for producing bio-oil is 52% PM, which increases total yield and cost-effectiveness[16]. Ultimately, 52% PM 2% dairy manure 3% camel manure and 43% sheep manure were identified as the ideal blending ratio for higher oil production at the lowest cost. The quality and nutrient content of biochar were improved by co-pyrolyzing PM, particularly chicken litter, with rye grass. This process increased the value of fixed carbon in the char and improved energy retention[17]. Up to 49% of the char yield was obtained from this study, and the produced char contained higher phosphorus and potassium than the original manures. The yield and characteristics of biofuel were greatly impacted by the co-pyrolysis of chicken manure with pine and oak wood. Depending on the type and quantity of wood, the study discovered that the optimum oil yields were 51.1 wt% at 400–500°C, with different stability and composition[18]. The combination of rice husk and chicken manure was examined by Espindola *et al.*, who found that there was a beneficial synergistic impact at mixing ratios higher than 20%. The best results were obtained at a 40% rice husk ratio, which resulted in maximal conversion[19]. Synergy during the co-pyrolysis process refers to the positive interaction that occurs when two or more different feedstocks are pyrolyzed together, leading to product yields or qualities that differ from the simple sum or average of their individual pyrolysis behaviours. With energy density of 5500–6000 kcal/kg, another study investigated the co-pyrolysis of urban plastic trash and chicken manure for the production of high energy char. In addition to improving energy efficiency, this technique provides a clean-burning substitute for coal[20].

The kind of reactor that is utilized for co-pyrolysis has a significant impact on the process since it affects the properties of heat transmission, particle contact, and volatile residence time. Compared to other pyrolysis technologies, the fixed bed pyrolysis system has a number of environmental benefits, especially when it comes to waste management, product yield, and efficiency. This technology is distinguished by its capacity to reduce emissions and energy consumption while transforming a variety of waste materials into useful products. Fixed-bed reactors are capable of producing large quantities of useful products. For example, under ideal circumstances, scrap tire pyrolysis produced an oil yield of 64 wt%[21]. A char yield of 72.62 wt% was obtained in the pyrolysis of municipal solid waste, indicating the effectiveness of the system in turning trash into useful byproducts[22]. Due to their simple design, ease of material handling, high conversion efficiency, reliable operation, cost-effectiveness, and well-defined residence time, fixed bed reactors were mostly used for the pyrolysis of PM[23-25]. Furthermore, it is possible to assume that the use of fixed bed reactors can have good synergy in the co-pyrolysis process due to the better particle interaction and mixing. Moreover, the majority of co-pyrolysis research has concentrated on analyzing synergistic effects and the properties of the pyrolysis yield. As a result, there are very few studies that examine the characteristics of the solid and liquid products that are produced during the co-pyrolysis process.

Given that poultry operations produce a lot of PM annually and that disposing of this waste is a major concern for both agriculture and environmental activities. PM was chosen for co-pyrolysis in this investigation together with SB since it may be a feedstock with significant promise for the energy sector. In order to improve the quality of the biochar and oil products, this work presents a unique method for the co-pyrolysis of PM with different biomass feedstocks in a fixed bed reactor. Along with the method of selecting biomass type for the co-pyrolysis process with PM, another element of novelty is the examination of the effect of feedstock on the resulting products. The results that are presented and their importance also exhibit uniqueness.

Experimental Section

Materials

The required amount of PM used for the pyrolysis experiment and feedstock analysis was collected from a local farmer in the suburban area of Coimbatore District, India. The PM was purified, cleaned with purified water, and dried in open sunlight for two days. SB representing agricultural biomass used for co-pyrolysis work is also collected from local sugarcane juice center in Coimbatore, India. After cleaning and drying, both the materials were stored in a plastic bag. Before pyrolysis experiments, both the feedstocks were further oven dried for 6 h maintained at 110°C. To ensure homogeneity, the dried samples were crushed into fine elements sieved. For the pyrolysis process, a feedstock with a minimum diameter is typically recommended to get maximum heat transmission[26, 27].

Reactor set up

The fixed bed pyrolysis reactor system involves various critical components and operational factors that impact the efficiency and product yield. This reactor type is generally utilized for the conversion of different feedstocks, such as agro waste, plastic waste, and tyre waste. The reactor is surrounded by an electric heater having an internal diameter of 50 mm and a length of 100 mm. The reactor is heated at the rate of 15 °C/min and the heating rate was controlled by an autotransformer. The reactor is completely insulated, hence; the supplied heat is effectively used to heat the feedstock materials. The reactor can be opened from the top, and it is tightly sealed using a bolt and nut assembly. The outlet pipe is connected with the top of the reactor, whereas the evolved gases were passed through it, and another end of the pipe is connected with the condenser unit. The condensation process was performed with the adequate ice water maintained at the temperature of 0°C.

Pyrolysis experiment

For individual pyrolysis experiments, 100 g of individual feedstock are loaded inside the reactor, and their yields are assessed by changing bed temperature from 350°C to 650°C. For co-pyrolysis experiments, the components were combined in different proportions, with SB mass percentages of 0, 20, 40, 50, 60, 80, and 100 wt%. The combination of PM and

SB for co-pyrolysis is primarily aimed at achieving synergistic effects that enhance the quality and yield of pyrolysis products. PM is rich in nitrogen, lipids, and minerals, but it has high ash content and produces oil with poor stability and unpleasant odour due to nitrogenous compounds. In contrast, SB is a lignocellulosic biomass containing abundant cellulose, hemicellulose, and lignin, which are rich in hydrogen but low in nitrogen and ash. When co-pyrolyzed, the hydrogen-rich volatiles from bagasse facilitate hydrogen transfer reactions that stabilize oxygenated and nitrogenous intermediates from PM, leading to improved deoxygenation, reduced nitrogen content, and enhanced hydrocarbon formation. Moreover, bagasse improves thermal behaviour and feedstock fluidity, ensuring better heat transfer and uniform decomposition process. This interaction not only increases oil yield and calorific value but also reduces gas pollutants, making co-pyrolysis a more efficient and sustainable approach for converting agricultural and animal wastes into renewable energy resources.The individual blended feedstocks utilized for this work were labeled as PM, PM80SB20, PM60SB40, PM50SB50, PM40SB60, PM20SB80 and SB. The projected yields and the synergistic impacts on the yields were compared. At the end of each pyrolysis process, char component was gathered once the bed was cooled to the atmospheric temperature. For that, a high-precision balance was used. The oil component collected at the bottom of the vessel is measured and recorded. The amount of gaseous fractions was assessed using material balance method. The expected yields were calculated using Eq. (1) based on the yields obtained from PM and SB[26]. Three separate tests were performed on each sample to ensure repeatability.

$$Y_{Predicted} = W_{PM} \times Y_{PM} + W_{SB} \times Y_{SB} \quad \dots (1)$$

Where,

$W_{PM} - Experimental\ yield\ from\ poultry\ manure$

$W_{SB} - Experimental\ yield\ from\ sugarcane\ bagasse$

$Y_{PM} - Mass\ proportion\ of\ poultry\ manure$

$Y_{SB} - Mass\ proportion\ of\ sugarcane\ bagasse$

Further equation (2) was used to find the yield of pyrolysis products.

$$Yield\ (wt\%) = \frac{Yield\ of\ desired\ product\ (oil\ or\ char\ or\ gas) in\ grams}{feedstock\ in\ grams} \quad \dots (2)$$

Characterization study of the feedstock and product

The suitability of the feedstock was assessed by proximate and ultimate analysis. The analyses were carried out in a muffle furnace under certain temperatures as per ASTM standards. The amount of various components was analyzed using the following Eqs (3-6). The elements in the feedstocks were assessed by the Elementar Analyzer (EA 2400 Series II).

$$\%M = \frac{sample\ weight\ before\ drying - sample\ weight\ after\ drying}{sample\ weight\ before\ drying} \times 100 \quad \dots (3)$$

$$\%VM = \frac{oven-dried\ sample\ weight - remaining\ sample\ weight\ after\ burning}{oven-dried\ sample\ weight} \times 100 \quad \dots (4)$$

$$\%A\ (air - dried\ sample) = \left(\frac{W_1}{W_2 \times \frac{T}{100}}\right) \times 100 \quad \dots (5)$$

Where W_1 – *weight of ash*, W_2 – *initial weight of sample* and *T* – *percent of total solid*

$$\%FC = 100 - (\%M + \%VM + \%A) \quad \dots (6)$$

Apart from the feedstock, the produced pyrolysis oil, char, and gaseous components were analyzed and reported. Prior to the analysis the aqueous phase from pyrolysis oil was separated by high-speed centrifuge. Bomb calorimetry (Parr-6772) was used to determine heating value and combustible sulfur levels using standard methods. The physical characteristics of the oil such as density, viscosity, pH value and flash point were found by a standard Redwood viscometer (SICBRV-01), digital pH meter (LMPH10, LABMAN) and Cleveland open cup apparatus. The elemental analysis of the produced char was also done using EA 2400 Series II Elementar Analyzer. The elements present in the evolved gas fractions were identified by a gas chromatography (Shimadzu gas analyzer, GC-2014).

TGA analysis

The thermogravimetric (TG) analysis for the PM and SB was carried out using simultaneous thermal analysis (TGA701). According to the recent research, 800°C is the ideal temperature for pyrolyzing biowastes since it maximizes cracking efficiency and reduces the excess tar generation[28,29]. In order to keep an inert environment, 10 mg of PM and SB was put in an alumina container and heated to 800 °C at a rate of 20 °C/min while being supplied with 100 mL/min of nitrogen. Data analyzed by the software were used to create the TG and derivative thermogravimetric (DTG) curves.

Results and Discussion

Analysis of feedstock

Table 1 list out the proximate and ultimate analysis of the selected feedstocks. In general, proximate analysis of the feedstock is used for the evaluation of the burning properties[30]. The analysis shows that PM and SB have a moisture content of 1.9 wt%. According to Asadullah *et al*. the feedstock having lower moisture (>10 wt%) is more suitable for the pyrolysis reaction[31]. Since, higher moisture in the feedstock restricts the heat transfer rate and thermal conversion efficiency. Compared to PM, SB has a higher volatile matter of 81.0 wt%. Generally, biomass with higher volatile matter is preferred for the pyrolysis reaction, since the material with higher volatile matter is more reactive[32]. The ash content of the PM and SB was recorded as 7.3 wt% and 2.9 wt%. Compared to SB, PM has higher ash content, which is more appropriate for the pyrolysis. Higher ash in the feedstock reduces the burning rate and increases fouling and slag formation. According to the ultimate analysis, the samples have a considerable amount of carbon and hydrogen content. This finding indicates that pyrolysis of PM and SB produces less SOx and NOx since the S and N content is relatively low. The lignocellulosic analysis of the feedstocks shows that both the materials have higher cellulose and hemicellulose content than lignin, which favors the yield of higher oil products. Based on the above analysis, it came to know that the selected PM and SB can be a suitable feedstock for this work.

Table 1 — Characteristics of PM and SB

Property	PM	SB	ASTM Standard
Proximate analysis (wt%)			
Moisture	1.9	5.2	D3173
Volatile matter	69.1	81.0	D3175
Ash	7.3	2.9	D3174
Fixed carbon	21.7	10.9	By Difference
Ultimate analysis^ (wt%)			
Carbon	35.55	45.20	D5373
Hydrogen	4.91	5.83	D5373
Nitrogen	4.53	0.22	D5373
Sulfur	0.81	0.04	D5373
Oxygen	54.21	48.71	By difference
Lignocellulosic analysis			
Cellulose	22.3	48.3	-
Hemicellulose	20.1	38.1	-
Lignin	6.0	11.1	-
Extractives	51.6	2.5	-

^Ash free basis

Thermal degradation behaviour

The PM and SB samples were subjected to TGA to identify the distinct mass loss phases occurring during pyrolysis. The corresponding DTG curves, which represent the rate of thermal decomposition derived from the mass loss profiles, were analyzed and are presented together in Fig. 1. The analysis allowing identification of distinct decomposition stages such as moisture evaporation, devolatilization, and char formation. The figure illustrates that mass decay in the thermolysis process of PM took place in three stages. Initially, the water molecules in the form of moisture content evaporate between 0°C and 120°C[33]. The presence of cellulose and hemicellulose breaks down beyond 160°C and it continues till it reaches 340°C[34]. The carbonization and breakdown of lignin in PM, as well as the subsequent cracking of proteins and lipids, are primarily responsible for the third area (>360ºC to 545ºC)[35]. The breakdown of mineral salts and metal oxides was categorized as occurring in the final stage. Based on TGA analysis, the primary breakdown of the constituents was identified as 200°C to 545°C. It is

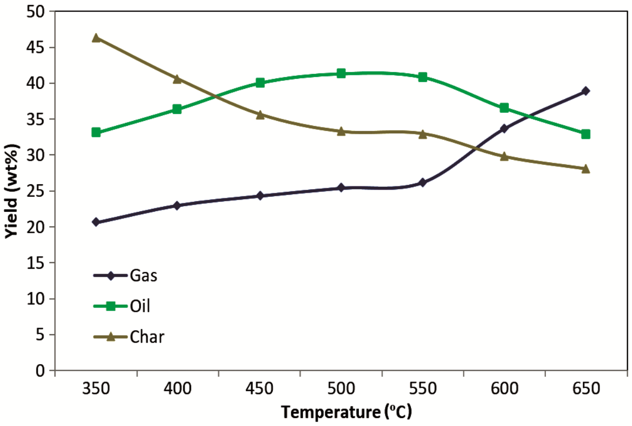

Fig. 1 — TGA and DTG curve of PM and SB

clear from the TGA analysis of the SB that the SB residue decomposed at four different stages. The DTG curve clearly demonstrates that the elimination of water molecules and extractives from the SB sample results in a minimal mass loss of about 9% below 210°C. After 210°C, there is a significant mass loss, with an average mass loss of 50% occurring between 210 and 415°C. In this step, the maximum mass loss ensued at 400°C with the decomposition of cellulose and hemicellulose. This zone is generally known as active pyrolysis. Additionally, mass loss of about 26% exists for temperatures between 420ºC and 480°C. In this zone some amount of lignin is also decomposed. Above 450ºC the decomposition rate of the biomass molecules gradually decreased, and almost no degradation was reported around 800ºC. This stage is called passive pyrolysis zone. After 800°C, for both PM and SB, a small amount of residue was identified, which resembles the ash content of the feedstock.

Pyrolysis of poultry manure and sugarcane bagasse

The aim of these works was to examine the pyrolysis products that were produced by pyrolyzing samples of PM and SB. Subsequently, the yield percentages were compared with those derived via co-pyrolysis of PM and SB and theinfluence of the process on the enhancement of the products' quality and energy value was examined.

Individual pyrolysis of PM

Temperature is thought to be the most significant factor influencing the yields of pyrolysis process. The primary purpose of temperature is to supply the necessary heat to breakdown biomass constituents. The impact of temperature on the yield of oil, char, and non-condensable gas is shown in Fig. 2. In comparison to other tested temperatures, it was found that the production of total pyrolysis oil was highest at 500°C. The production of additional non-condensable gases was enhanced by temperature increases beyond 500°C, which reduced the char yield and overall oil yield. The reduction in char yield demonstrated that pyrolysis at elevated temperatures improved PM conversion. The higher gas yield at higher temperatures could be because the heavy-molecular-weight molecules in the pyro-vapours underwent subsequent cracking or reforming[36]. At 500°C the produced amount of oil, char and gas from PM pyrolysis are 41.3 wt%, 33.3 wt% and 25.4 wt%, respectively. The yield of char at 350°C is 46.3 wt%, which was reduced to 28.1 wt% at 650°C. Following their separation into an oil and aqueous phase, the condensable volatiles were gathered as the entire pyrolytic liquid[37]. As a result, the PM thermal pyrolysis investigation verified that the ideal temperature for producing a maximum of 41.3 wt% pyrolysis oil was 500°C.

Individual pyrolysis of SB

The yield of products from the pyrolysis of SB is displayed in Fig. 3 as a function of the final temperatures, which range from 350 to 650°C. Higher oil yields are observed at intermediate temperatures of 450 to 600°C. The output of oil during SB pyrolysis first rises as the temperature rises, reaches a peak, and then falls[38]. The outcomes of the current investigation likewise show similar patterns. As the temperature rises to 500°C, the production of bio-oil increases to 40.2 wt%. It then falls to 36.8 wt% when the reactor reaches to 650°C. At higher temperatures, the yield of oil decreases because of secondary cracking reactions of the evolved gases, which result in increased gas components, and secondary decomposition of char[39].

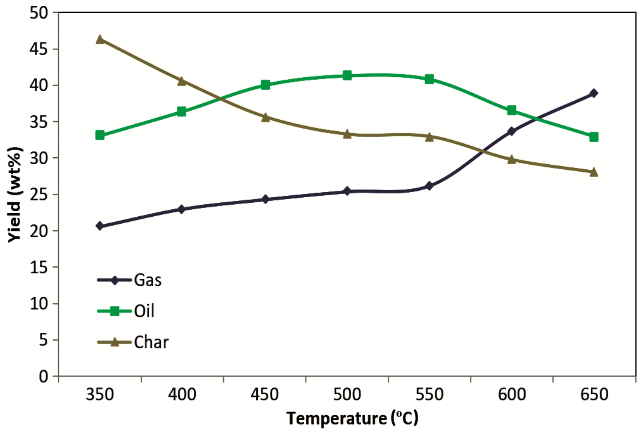

Fig. 2— Effect of temperature on PM pyrolysis yield

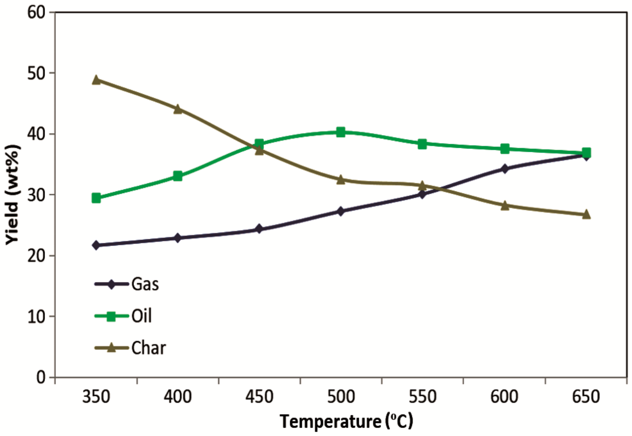

Fig. 3— Effect of temperature on SB pyrolysis yield

Based on the current investigation, it can be said that the oil yield reached its peak at the ideal temperature of 500°C. According to the figure, when the temperature changes from 350 to 650 °C, the char yield drop from 48.9 wt% to 26.7 wt%. Increased SB breakdown and degradation of secondary char residue may be the cause of the decreased char production[40]. Increase of bed temperature increased the gas production from 21.7 wt% to 36.5 wt%.

Evaluation of synergistic effects on yield

Through co-pyrolysis, two different solid feedstock combinations can be transformed to generate fuels and value-added goods in a synergistic manner. The phrase "synergistic effect" refers to the ability of binary, ternary, or multiple combinations of different feedstocks to generate an effect that is either larger or lower than that which is computed or estimated from the weighted value of each feed material[41]. A change in feedstock blend ratio is one of the key elements affecting the synergistic effects[42,43]. Fig. 4 displays the synergistic effect observed when comparing the computed with the experimental value. Additionally, the estimated and experimental are denoted by the dotted and continuous lines, respectively. In comparison to prediction data, Fig. 4 shows that co-pyrolysis of PM with SB reduces char and gas yield while improving oil phase. Blending 20%, 40%, and 50% SB with PM enhanced the yield of oil and decreased char and gaseous components. Adding 40% SB (PM60SB40) produced a maximum of 43.7 wt% oil yield, which shows a 6.95% increment compared to predicted value. On the same condition, the yield of char and gas components was decreased up to 6.76% and 2.91%. This suggests that pyrolyzing combined PM and SB has a synergistic effect that results in both lower char and higher oil yield. These findings can be understood by the notion that the co-pyrolyzing PM and SB create free radicals and exchanged hydrogen atoms, which causes a cross-reaction between them[44]. This impact may hinder the breakdown of functional groups bound in the cellulose arrangement of the lignocellulosic material, preventing the release of lower-molecular gaseous products and promoting the production of higher-molecular oil phase[45]. Regarding gas production, the addition of 80% SB increased the gas yield to 29.1 wt%, which is 8.1% higher compared to the predicted value.

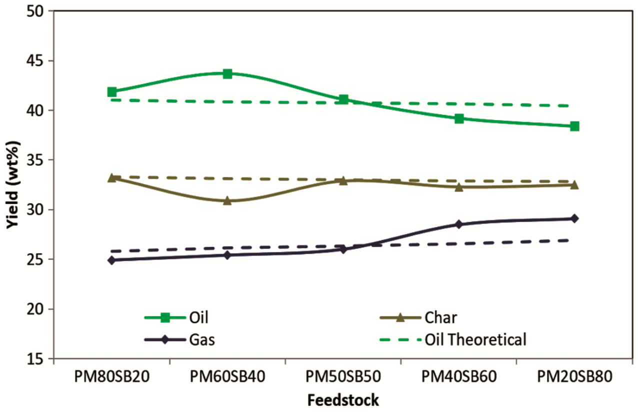

Fig. 4 — Synergistic evaluation

Characterization of pyrolysis products

Analysis of liquid

After being extracted from the liquid collector, the oil processed from PM, SB, and PM60SB40 was characterized and described in Table 2. Pyrolysis oil produced from SB has a higher carbon of 57.94 wt%. The N and ash content of the SB pyrolysis oil is 0.5 wt % and 0.05 wt% respectively. Any fuel that has lower levels of sulfur and nitrogen is more environmentally friendly since it produces fewer pollutants. The existence of lower O in the SB oil compared to PM oil increased its energy density to 25.10 MJ/kg. The primary cause of the water molecules is the reaction caused by the lignin component of the feedstocks. Increased oxygenated molecules in the oil may change its fluidity, flame temperature, and stability[46]. The nitrogen content of the PM pyrolysis oil is 4.92 wt%, which shows the emission of higher NOx while burning. The reported calorific values of the oils are higher than those found by the literature[47] for different pyrolysis oils. The densities of the PM and SB pyrolysis are 1025 kg/m^3 and 1040 kg/m^3 respectively. The viscosity of the PM and SB pyrolysis oils is 4.5 cSt and 12.3 cSt respectively. Higher viscosity of

Table 2 — Properties of the pyrolysis oil

Properties	PM	SB	PM60SB40	Unit
Density	1025	1040	1030	(kg/m^3)
Kinematic viscosity at 40 °C	4.5	12.3	7.6	cSt
Flash point	110	72	95	°C
pH	4.6	3.1	4.1	-
Calorific value	20.08	25.10	22.36	MJ/kg
Elemental analysis				
C	55.03	57.94	57.01	wt%
H	5.33	7.92	6.27	wt%
N	4.92	0.5	2.92	wt%
S	0.32	0.05	0.2	wt%
$O^{\#}$	34.4	33.59	33.6	wt%

$^{\#}$by difference

the SB fuel leads to poor atomization when it is injected by the injector. At normal atmospheric conditions, the pH value of the PM and SB oil was 4.6 and 3.1, respectively. The lower pH value of the oil should be exchanged before being used as fuel for heating applications since it can corrode metal components[48]. The flash point was estimated as 110°C and 72°C or PM and SB oils. The higher flash point of the PM oil shows that it can be stored safely at normal temperature. The physiochemical properties of the raw PM oil changed with respect to the addition of SB. Table 2 also illustrates the changes in its physiochemical properties. The heating value of the PM60SB40 oil was found to be 22.36 MJ/kg.

Analysis of char

Table 3 provides an overview of the characteristic feature of the chars obtained during the various pyrolysis runs. The char produced by the SB pyrolysis had superior qualities for energetic uses compared to that produced by the PM pyrolysis: the SB char had a higher fixed carbon content and less ash, which resulted in a greater energy density. Additionally, there was less sulfur and nitrogen in the SB char, which are pollutants in fuel. The carbon and hydrogen content of the SB is also high compared to PM pyrolyzed char, which is proportional to the higher carbon and hydrogen content of the raw SB. The heating value of the produced PM and SB char is 12.5 MJ/kg and 23.4 MJ/kg, respectively. As can be shown, PM60SB40 char had a comparatively higher volatile content (22.5 wt%), fixed carbon (46.1 wt%), and lower ash content (30.3 wt%) compared to the predicted average. It can also be understood from the analysis that the C and H of the PM60SB40 is 3.92% and 2.1% more compared to the prediction. Adding a significant amount of SB to PM would have beneficial synergistic effects from the viewpoint of char. The primary cause of the synergistic effects was the production of free radicals as a result of PM devolatilization[49, 50].

Table 3 — Analysis of char components

Property	PM	SB	PM60SB40	Predicted average
Proximate analysis (wt%)				
Moisture	1.0	1.7	1.1	1.3
Volatile matter	17.1	24.2	22.5	19.9
Ash	47.6	15.3	30.3	34.7
Fixed carbon#	34.3	58.8	46.1	44.1
Ultimate analysis^ (wt%)				
Carbon	46.30	68.41	57.3	55.14
Hydrogen	3.28	3.52	3.44	3.37
Nitrogen	2.91	0.82	1.96	2.07
Sulfur	0.56	0.01	0.30	0.34
Oxygen#	46.95	27.24	37.00	39.06
Heating value (MJ/kg)	12.5	23.4	17.60	16.86

#by difference ^Ash free basis

Analysis of gaseous products

The properties of the feedstock material and its combination will determine the composition of the non-condensable gas. Carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H), and low molecular weight hydrocarbons (HC) are the primary combustibles in non-condensable gases. Determining the quality of these gas fractions required a compositional analysis. The main constituents of the gas generated by the individual pyrolysis of PM and SB and the co-pyrolysis of PM60SB40 are shown in Fig. 5. In order to find its constituents, the gas samples were analyzed by the GC method. Individual pyrolysis of PM consists of 19.8 mol% CO, 41.8 mol% CO_2, 13.8 mol% CH_4, 6.5 mol% C_nH_n, 1.7 mol% O_2, and 16.3 mol% H_2 in the total gas components. On the other side, SB pyrolysis gas consists of 41.6 mol% CO, 35.4 mol% CO_2, 12.3 mol% CH_4, 2.1 mol% C_nH_n, 2.8 mol% O_2, and 5.8 mol% H_2. The gas fraction of the PM60SB40 is also analyzed and found 29.6 mol% CO, 40.1 mol% CO_2, 12.8 mol% CH_4, 5 mol% C_nH_n, 2.1 mol% O_2 and 10.4 mol% H_2. The total concentration of CO and H in the gas strongly depends on the temperature of the pyrolysis process. Both H and CO found in the gas components can be used as syngas for the production of liquid fuel, and H can also be used to upgrade pyrolysis oil.

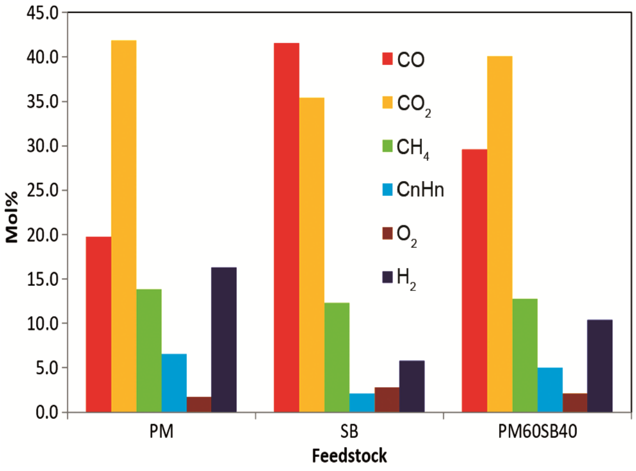

Fig. 5 — Non-condensable gas fractions

Limitations and social benefit of the work

Despite its potential as a renewable energy feedstock, the pyrolysis of PM faces several significant limitations that affect process efficiency and product quality. The higher ash and moisture reduce its heating value and lead to incomplete volatilization. The higher nitrogen and sulfur contribute to the formation of toxic nitrogen- and sulfur-containing compounds, which require additional gas cleaning or upgrading steps. Furthermore, the mineral-rich ash often causes catalytic cracking, agglomeration, and reactor fouling, complicating continuous operation. Additionally, feedstock heterogeneity, odor issues, and the need for pre-drying issues exist. Therefore, co-pyrolysis strategy is recommended to overcome these technical and environmental challenges.The pyrolysis of PM offers several social benefits alongside its environmental and economic advantages. By converting a malodorous and pathogen-laden waste into valuable products, pyrolysis helps improve community hygiene and sanitation in poultry-farming regions, reducing odour, flies, and disease transmission risks. This waste-to-energy approach supports rural employment generation through the establishment of decentralized pyrolysis units, promoting entrepreneurship and livelihood opportunities for small-scale farmers and local workers. Additionally, the production and utilization of char as an organic soil amendment encourage sustainable farming practices, enhance soil health awareness, and reduce dependence on costly chemical fertilizers. Pyrolysis-based waste management also strengthens public perception of the poultry industry by mitigating pollution and demonstrating environmental responsibility. Overall, adopting PM pyrolysis contributes to cleaner rural environments, improved public health, energy access, and socio-economic development, aligning with India’s broader goals of rural sustainability and circular bioeconomy.

Conclusion

A combination of PM and SB showed a promising feedstock for biofuel production. In this work, the selected two feedstocks were combined in various mass ratios to assess the effects of varying the quantities of SB and PM on the production of pyrolysis biofuel. The product yields were significantly impacted by the weight percentage change of SB and PM. According to this study, pyrolysis of these components offers the possibility of producing high-grade pyrolysis oil, with a greater oil output of 43.7 wt% at 40% blend of SB. The synergistic effects of the co-pyrolysis process were examined, and positive synergy was recorded at 40% SB, which demonstrated a 6.95% higher oil production than other combinations as compared to the predicted value. In terms of gas production, adding 80% SB raised the gas yield to 29.1 w%, which is 8.1% more than what was predicted. In comparison to biomass pyrolysis, the pyrolysis oil derived from PM, SB, and PM60SB40 was shown to be a promising biofuel candidate with a heating value of 20.08 MJ/kg, 25.10 MJ/kg, and 22.36 MJ/kg, respectively. A higher heating value indicates that it can be improved to be used as fuel for internal combustion engines and utilized directly as boiler furnace oil. To improve waste treatment and utilization, further research may be done to analyze the reaction kinetics and applications.

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