

## Research Article

# Valorization of Hazardous Materials along with Biomass for Green Energy Generation and Environmental Sustainability through Pyrolysis

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Increased population growth, industrialization, and modern culture create a variety of consequences, including environmental pollution, heavy metal accumulation, and decreasing energy resources. This perilous position necessitates the development of long-term energy resources and strategies to address environmental threats and power shortages. In this study, an investigation into the use of castor seed oil cake and waste tyres as a feed material for the copyrolysis process for yielding maximum oil production was performed. The copyrolysis experiments were performed by changing the mass percentage of waste tyres with oil cake to make different ratios of 100:0, 75:25, 50:50, 25:75, and 0:100. At 50:50 ratio, the maximum positive synergy on oil production was obtained. At that condition, a maximum of 59.8 wt% oil was produced and characterized to analyze its physiochemical properties. The coprocessing of the selected two feed materials enables the stabilization of the oil, as the produced oil has a lower oxygen content with a maximum heating value of 38.72 MJ/kg. The Fourier transform infrared spectroscopy (FTIR) and gas chromatography-mass spectrometry (GC-MS) analysis of the oil showed the existence of aromatic hydrocarbons and phenolic elements. Adding waste tyres to the biomass improved the quality of the oil by increasing carbon content with reduced oxygen content.

## 1. Introduction

Biofuels and biochemicals made from renewable resources are a crucial driver for sustainable societies. The use of waste material valorization has been growing fast for the past three decades due to increased global warming, the negative environmental impact of fossil fuel consumption, energy demand, and the availability of waste materials [1]. In this background, it is essential to analyze how to develop current energy recovery processes with minimum environmental effect.

Energy is the essential one for the growth of industries and global economy. It supports the operation of industries and transportation for the development of the nation. The depletion of fossil fuel resources, the growing population, and environmental concerns have all prompted research into alternative fuels [2]. The consumption of biofuel is increasing steadily from 2% to 27% by 2050. Biomass is cheap and abundant. It is a renewable and cost-effective resource that emits very little CO<sub>2</sub> into the environment. Generally, it is a clean alternative source. The CO<sub>2</sub> generated by burning biomass can be captured during the photosynthesis process. Hence, the sustainability of the world can be achieved by minimizing global warming [3]. Biomass conversion can be accomplished using a variety of processes, which are broadly classified as thermochemical and biochemical conversion [4]. Pyrolysis of biomass provides a viable option for producing energy-rich medium-to-high grade liquid fuels. Pyrolysis has received a lot of attention due to its higher efficiency [5]. Pyrolysis oil is a key product of the pyrolysis process [6]. Despite its potential as a renewable energy source, bio-oil confronts a number of technical challenges, such as higher acidity, higher viscosity, higher water content, higher corrosive nature, and lower calorific value [7]. Due to these unfavourable properties, the bio-oil is unstable during storage [8].

Castor seed oil cake is considered as a solid biomass left over from the process of extraction of castor oil in a huge amount. India is a major producer of castor oil. 96% of India's total castor seed production comes from Gujarat, Rajasthan, and Andhra Pradesh. It is the most useful vegetable oil, having almost 90% ricinoleic acid [9, 10]. Castor seed oil cake is generally unsuitable for animal feed since it has some toxic chemicals and allergens [11]. Despite the fact that numerous ways have been identified to recycle these cakes [12], their usage as fertilizer is still restricted. In this context, pyrolysis of these wastes for bio-oil production has been identified as a promising method due to its high global output. Previously, a lot of literature focused on the usage of various pressed oil cakes obtained from sunflower [13], rapeseed [14], safflower [15], soybean [16], mustard [17], and neem [18] for bio-oil production. Gerçel [13] conducted pyrolysis experiments on sunflower oil cake. The author investigated the impact of sweep flow rate and reaction temperature on the yield. In this study, a maximum of 48.69 wt% bio-oil was obtained at 550°C, 100 cm<sup>3</sup>/min sweep gas flow rate, and 5°C/s heating rate. David and Kopáč [19] produced bio-oil from rapeseed cake through a catalytic pyrolysis process. The produced oil has higher fractions of

aromatic and phenolic elements. The catalytic pyrolysis produced bio-oil with lower oxygen content. Previously, castor seed oil cake has been used by various authors for producing oil [20], char [21], chemicals [22], and functional materials [23]. Recently, Silva et al. [24] derived biochar from castor seed oil cake to be used as an absorber material for the treatment of waste water. The study also recommended the derived bio-oil to use as a fuel of the production of power [25].

Waste tyres on the other hand have become a major issue for the clean environment. The accumulation of waste tyres has been accumulating every year for the past two decades due to the dynamic growth of the automotive industries. Each year, around 1.5 billion tyres are produced, which ultimately end up in the trash. The waste volume is increasing at a rate of 12% per annum. In India, it is believed that 60% of waste tyres are disposed of through illegal dumping. The growing number of discarded tyres is posing a major hazard to the atmosphere. Waste tyres that have been illegally discarded or stacked pose a risk of uncontrolled combustion [26]. Pyrolysis of waste tyres is an effective method for sustainable development. Recycling waste tyres through pyrolysis is familiar and widely discussed by various authors [27–29]. Czajczyńska et al. [30] pyrolyzed waste tyres at different temperatures of 400, 500, and 600°C. The study produced pyrolysis oil with a low heavy metal level and recommended to use these oils for safe environment. Yazdani et al. [31] found the impact of temperatures on tyre pyrolysis. At 550°C, the higher liquid oil yield of 55 wt% was reached. Abdallah et al. [32] used an industrial-scale system to pyrolyze waste tyres, reporting maximum production of liquid oil of 45 wt%. Martinez [33] conducted waste tyre pyrolysis experiments on a twin-auger reactor to examine the process variables on yields. During this study, 45 wt% of liquid oil was acquired at 475°C under the feedstock flow rate of 1.16 kg/hr and sweep gas flow rate of 300 mL/min. The study discovered that temperature, rather than feeding rate, swept gas flow rate, and residence time, is the significant factor in determining the maximum yield of liquid oil. In a conical spouted reactor, truck tyres were pyrolyzed by Lopez et al. [34]. The authors found that 475°C was the ideal temperature for complete decomposition of tyres to produce higher liquid oil. Williams [35] studied the liquid, char, and gas qualities produced through the pyrolysis of used tyres. The study focused on reaction conditions, product distribution, and its characterization. The study also suggested that it is important to emphasize the pyrolysis behavior, reaction kinetics, and mechanism to gain maximum material conversion.

Apart from individual pyrolysis, copyrolysis of lignocellulosic material with tyres gives a solution for waste management. Copyrolysis of biomass with other materials that are widely available could be a cost-effective way to produce biofuels. Copyrolysis adjusts the carbon, hydrogen, and oxygen contents of the feedstock and produces a favorable synergistic effect on improving the quality of the bio-oil [36]. Khan et al. [37] discovered that copyrolysis of cotton stalk and waste tyre at 550°C yielded the most carbon and hydrogen-rich bio-oil. Wang et al. [38] carried out

copyrolysis experiments with pine wood bark and waste tyres by changing the weight ratio of the tyres from 0 to 100%. The study found that the biogas produced at a higher biomass weight ratio had a higher concentration of H<sub>2</sub> and CO. Sanahuja-Parejo et al. [39] performed pyrolysis experiments on grape seeds and waste tyres with calcium oxide catalyst. The author found a synergistic effect on bio-oil yield. The oil content produced in this study had favorable aromatics and hydrocarbons. The above findings also matched with Cao et al. [40] who produced bio-oil through copyrolysis of wood and tyre with enhanced quality due to the positive synergistic effect. Martínez et al. [41] also looked into the copyrolysis characteristics of pine wood chips mixed with scrap tyres. When comparing biomass bio-oil and the bio-oil made by the copyrolysis process, the characteristics of the bio-oil made by copyrolysis increased dramatically. By varying the blend ratio, Uçar and Karagöz [42] copyrolyzed pine nut shells with waste tyres at 500°C. In this study, increased tyre fractions increased the carbon content in the produced oil.

The goal of this paper is to find the sustainable way to the waste tyre recycling process. In this path, this study was planned to investigate the copyrolysis of castor seed oil cake and waste tyres with an emphasis of higher liquid yield. The synergistic effect is basically dependent on the feedstock used for the process. According to the author's knowledge, there has been no work published with the combination of castor seed oil cake and waste tyres. The effect of the addition of tyre during pyrolysis of castor seed oil cake was investigated in this study with respect to yield. The yield was analyzed by increasing tyre material at the ratios of 75:25, 50:50, and 25:75 (biomass: tyre).

## 2. Materials and Methods

**2.1. Materials.** The castor seed oil cake was obtained from local oil mill in Coimbatore, India. The waste tyres were collected from a local vulcanizing centre in Coimbatore. Both materials were available in plenty at a very low cost. The seed cakes were dried initially for one week under direct sunlight and then crushed to reduce their size. The steel wires and fabrics were removed carefully from the collected waste tyres and cut into small pieces. Both feedstocks were maintained at uniform sizes of 0.5–2 mm.

**2.2. Characterization Study.** In order to find the volatile matter in both feedstocks, proximate and ultimate analyses were carried out according to ASTM standards. The thermogravimetric analysis (TGA701, LECO Corporation, Michigan) was used to find the pyrolysis behavior of the materials using the TGA701 thermogravimetric analyzer. The ultimate analysis of the sample was carried out by using a CHNS analyzer and the heating value of the samples was found by using a Paar-6772 bomb calorimeter. The functional groups in the bio-oil are analyzed by BRUKER Optik GmbH TENSOR 27 FT-IR spectroscopy. The spectra were obtained in the range of 400–4000 cm<sup>-1</sup> with 4 cm<sup>-1</sup> resolution. The THERMO GC-TRACE ULTRA VER: 5.0 and

THERMO MS DSQ II were used to qualitatively identify and quantify the organic elements in bio-oil. The column temperature is initially set to 60°C and heated to 250°C. Helium is used as a carrier gas for the analysis. The capillary column has a length of 30 m and a diameter of 0.25 mm. The ion source temperature is 220°C, and the peak corresponding to the element was obtained with reference to the NIST 11 library.

**2.3. Pyrolysis Reactor.** The fixed bed reactor has an internal diameter of 50 mm and a height of 30 cm. The reactor has a capacity of 200 grams per batch and 30 grams of the feed material was filled for each experiment. The reactor is heated electrically and can withstand up to 1200°C. The reactor is fully covered with insulating material (Chromel Alumel) to resist unwanted energy loss from the reactor bed. Two K-type thermocouples were fixed at the bottom and middle of the reactor. The heat input to the reactor is controlled by an autotransformer with a voltmeter and ammeter set-up. The exit of the reactor is connected to a water-cooled condenser, whereas the cooling water was supplied at 5°C.

**2.4. Experimental Procedure.** All the experiments in this study were conducted at 500°C. The process was carried out by changing the mass percentage of castor seed oil cake and waste tyre ratios such as 100:0, 75:25, 50:50, 25:75, and 0:100. Initially, individual feedstocks were pyrolyzed, and then, copyrolysis experiments were performed by changing the biomass tyre ratio. For each run, 30 g of sample was loaded and the yield was analyzed. All the experiments were carried out by heating the reactor at a rate of 20 K/min. Each run was conducted till no vapour was released from the reactor. At the end of each experiment, the reactor was cleaned. The condensable volatiles that pass through the reactor have condensed and converted into liquid form. The bio-oil was collected and stored. After the reactor reached atmospheric temperature, the char was collected. The collected samples were weighed and the gas fractions were found by remaining material balance.

**2.5. Synergistic Effect.** The synergistic effect on product yields was observed by comparing theoretical and experimental yields. The theoretical yield during the copyrolysis process was calculated by additivity rule [43] shown in the following equation:

$$YT = (W_1 \times \alpha_1 + W_2 \times \alpha_2), \quad (1)$$

where  $Y_T$  is the theoretical yield,  $W_1$  and  $W_2$  are the mass proportions of castor seed oil cake and waste tyres, and  $\alpha_1$  and  $\alpha_2$  are the experimental yields.

## 3. Results and Discussion

**3.1. Material Characterization.** Table 1 shows the basic characteristics of the castor seed oil cake and waste tyres. The castor seed oil cake and waste tyres have a higher amount of volatile matters. The higher volatiles in the material give

TABLE 1: Feedstock characteristics.

Parameters	Castor seed oil cake	Waste tyres	Standard
Volatile matter	68.3	64.1	ASTM D3175
Fixed carbon	14.3	23.4	By difference
Moisture content	8.12	0.9	ASTM D3173
Ash	9.28	11.6	ASTM D3174
Carbon	51.20	80.60	ASTM D5373
Hydrogen	7.11	7.23	ASTM D5373
Nitrogen	2.93	0.44	ASTM D5373
Oxygen <sup>#</sup>	38.73	9.91	By difference
Sulphur	0.03	1.82	ASTM D5373
Heating value (MJ/kg)	28.10	37.20	ASTM D445

<sup>#</sup>By difference.

confidence in the yielding of more bio-oil during volatilization. The presence of higher volatiles in the inveterate burning of fuel would be expedient. The moisture content of the material is within the permissible range (less than 10%). The ash content of both materials is high. Generally, the ash particle in the sample reduces the yield and quality of oil [40]. The ultimate analysis of the samples and products was done on an ash-free basis. The feedstocks are having higher amount of carbon (51.20% and 80.60%) and a lower amount of nitrogen (2.93% and 0.44%). Because there was low nitrogen and sulphur, the formation of SO<sub>x</sub> and NO<sub>x</sub> during pyrolysis would be reduced. In energy content point of view, the waste tyres have higher calorific value (37.20 MJ/kg) than castor seed oil seed cake (28.10 MJ/kg).

**3.2. Thermogravimetric Analysis.** This analysis is used to evaluate the thermal behavior of castor seed oil cake and waste tyres under a pyrolysis environment. For this, the feedstocks were heated from atmospheric temperature to 800°C in a nitrogen environment at 20°C/min heating rate. The biomass devolatilization begins earlier than waste tyres. The initial degradation started at 50°C, which represents the evaporation of moisture from the material. Around 10% of the weight was lost due to the moisture removal process. The decomposition of the oil cake took place in three stages [44]. At first, the lignin starts to decompose till 500°C. A major mass loss (70%) occurred between 225°C and 450°C representing the breakdown of cellulose and hemicellulose. At this temperature range, the cellulose and hemicellulose of the biomass material have decomposed rapidly and released a greater number of volatiles. After 500°C, castor seed oil cake is converted to carbon residue. At this point, lignin breakdown accounts for around 10% of the mass loss. The structure of waste tyres is not as complex as that of castor seed oil cake. The TGA of waste tyres has also been reported in the literature [45, 46] with three main steps: a first step of the process is related to

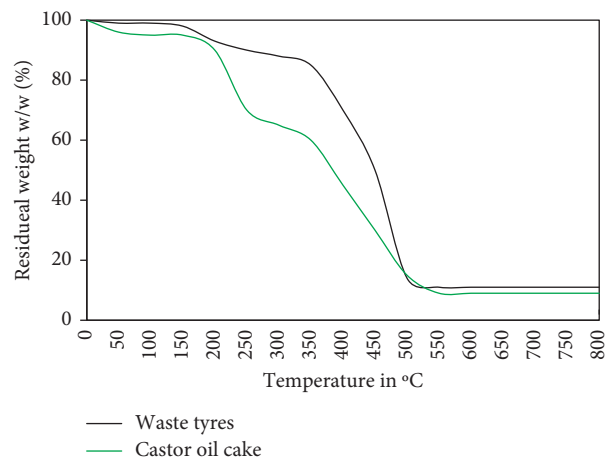


FIGURE 1: Thermogravimetric analysis of the feedstocks.

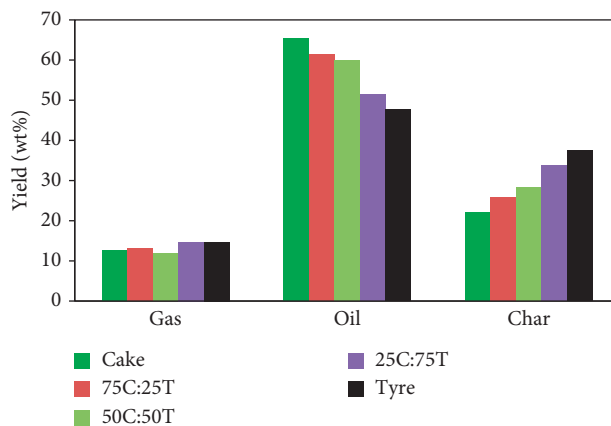


FIGURE 2: Experimental product yields performed at 500°C.

the pyrolysis of rubber additives, natural rubber, and synthetic rubber decomposition. From this analysis, it can be found that both the materials decomposed completely between 250°C and 500°C. At this temperature, the pyrolysis of castor seed oil cake and that of waste tyres overlap. As a result, radicals produced during the pyrolysis process may coexist at this temperature. So, for further experimental works, the temperature was fixed at 500°C. Figure 1 shows the TGA curve of the feedstock materials.

**3.3. Pyrolysis Product Yield.** Figure 2 shows the product yields obtained from individual and copyrolysis processes. The maximum oil products were acquired from castor seed oil cake. Overall, the oil production from both materials is high when compared to char and gas. The higher oil yield from biomass is attributed to the presence of higher volatile matters than waste tyres [47]. Compared to biomass, waste tyres produced more char. This is due to the existence of more ash in the tyres and carbon clack used for the formation of the tyre. During experimentation, the oil and char yield follows a linear tendency with the addition of increased tyre particles. The production of oil is decreased with increased char yield by increasing tyre materials. The fraction

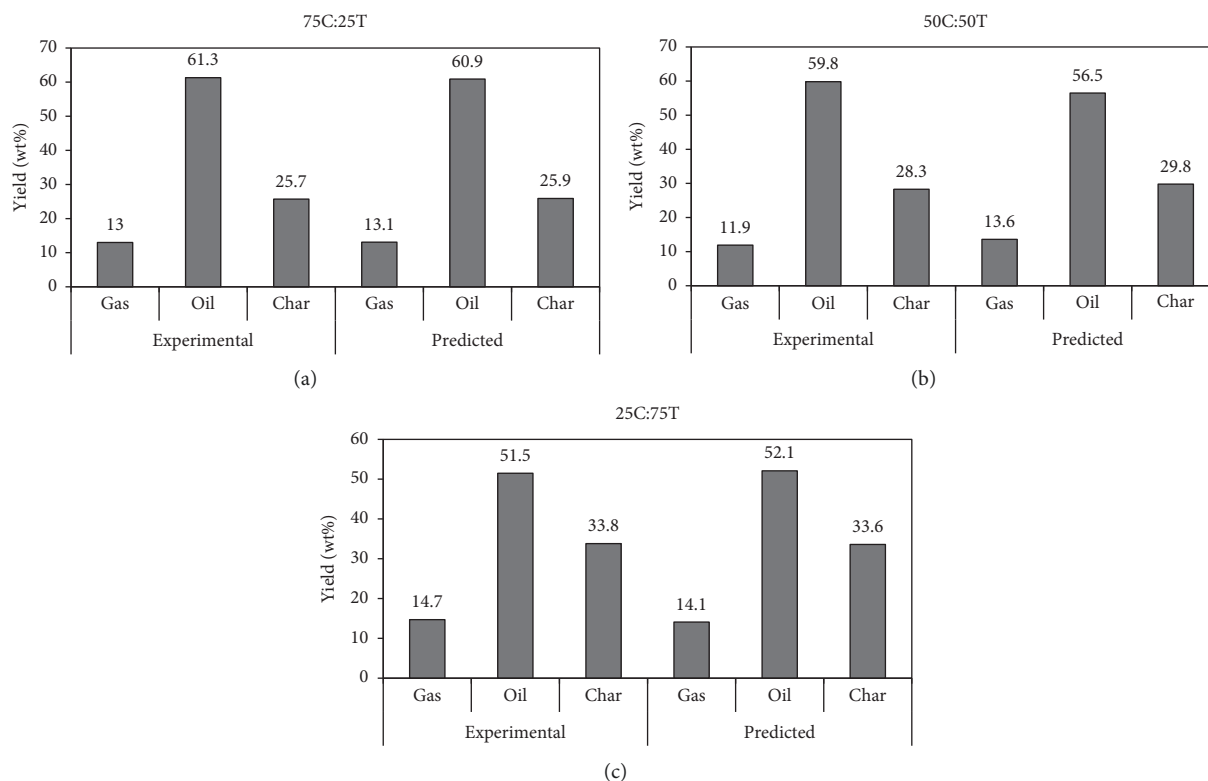


FIGURE 3: Experimental and theoretical product yields during copyrolysis performed at 500°C.

TABLE 2: Properties of copyrolysis oil.

Elements	Unit	Copyrolysis oil <sup>s</sup>	Diesel [53]
Density	kg/m <sup>3</sup>	925	850
Viscosity	cSt	3.82	3.9
Flash point	°C	35	57
pH	—	3.62	—
Carbon	wt%	78.35	86.5
Hydrogen	wt%	9.56	13.2
Nitrogen	wt%	0.50	0.02
Sulphur	wt%	0.92	0.24
Oxygen <sup>a</sup>	wt%	10.67	—
Heating value	MJ/kg	38.72	43.6
Empirical formula	—	CH <sub>1.453</sub> N <sub>0.0005</sub> O <sub>0.102</sub>	—

of oil varied from 65.3 wt% to 47.8 wt% and the char yield varied from 22.1 wt% to 37.5 wt%. The yield of gas fractions is similar for all of the feedstocks studied, ranging from 11.9 wt% to 14.7 wt%.

**3.4. Synergistic Analysis.** Figures 3(a)–3(c) show the comparison of theoretical and experimental yields during the copyrolysis process under different blends of biomass and tyres. The copyrolysis process at the proportions of 75:25 and 50:50 results in a slight decrease in gas and char yield, while the oil fractions increased significantly, which indicates a positive synergistic effect. At 75C:25T, the yield of oil increased by 0.66% compared to the predicted value. Likewise, the value was increased to 5.84% for the 50C:50T blend. This can be explicated by the exchange of hydrogen

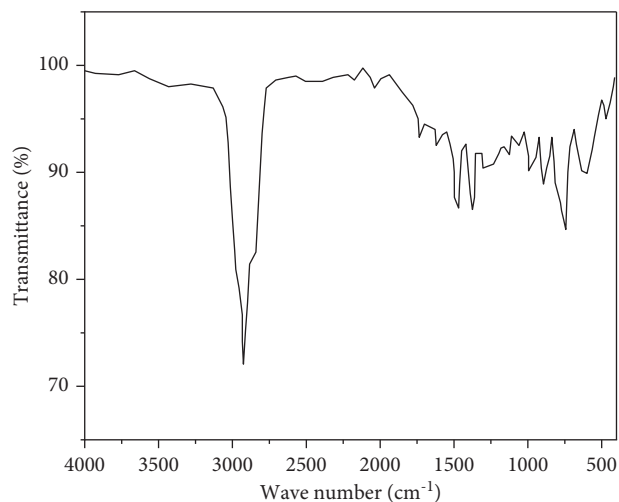


FIGURE 4: FT-IR analysis of the oil.

atoms and the creation of free radicals [48]. This creates a cross-reaction between biomass and waste tyres [49]. At 25C:75T blended samples, the positive synergy was observed for char and gas fractions, whereas the yield of char and gas was improved by 0.6% and 4.26%, respectively, with respect to the predicted value. Based on the results provided in Figure 3, it can be inferred that when the blend of oil cake and tyres surpasses 50:50, there is no evident synergistic effect on oil fractions. The experimental work conducted by Cao et al. [40], Uçar and Karagöz [42], Farooq et al. [50], and



TABLE 3: GC-MS analysis of oil.

RT/min	Compound name	Molecular name	% area
4.26	2-Furanmethanol	C <sub>5</sub> H <sub>6</sub> O <sub>2</sub>	0.18
4.94	Acetic acid	C <sub>2</sub> H <sub>4</sub> O <sub>2</sub>	4.04
5.60	Methanol	CH <sub>4</sub> O	2.14
7.11	2-Butanone	C <sub>4</sub> H <sub>8</sub> O	0.59
7.56	2-Methoxy-phenol	C <sub>7</sub> H <sub>8</sub> O <sub>2</sub>	2.87
8.21	Octanal	C <sub>8</sub> H <sub>16</sub> O	2.46
10.25	Phenol	C <sub>6</sub> H <sub>6</sub> O	0.81
11.12	2-Methoxy-4-(2-propenyl)-phenol acetate	C <sub>12</sub> H <sub>14</sub> O <sub>3</sub>	3.04
11.98	1-Hydroxy-2-pentanone	C <sub>5</sub> H <sub>10</sub> O <sub>2</sub>	2.93
12.09	Butanedial	C <sub>4</sub> H <sub>6</sub> O <sub>2</sub>	3.77
12.94	2-Methoxy-4-methyl-phenol	C <sub>8</sub> H <sub>10</sub> O <sub>2</sub>	0.98
13.52	Levoglucozan	C <sub>6</sub> H <sub>10</sub> O <sub>5</sub>	2.94
16.75	2,4-Dimethylstyrene	C <sub>10</sub> H <sub>12</sub>	0.74
17.01	2-Methyl-Naphthalene	C <sub>11</sub> H <sub>10</sub>	0.83
18.25	D-Limonene	C <sub>10</sub> H <sub>16</sub>	8.11
18.67	2,6-Dimethoxyphenol	C <sub>8</sub> H <sub>10</sub> O <sub>3</sub>	1.59
19.41	2,6-Dimethyl-Naphthalene	C <sub>12</sub> H <sub>12</sub>	0.66
20.08	Methylbenzene	C <sub>7</sub> H <sub>8</sub>	3.37
20.71	Methylene-cyclohexane	C <sub>7</sub> H <sub>12</sub>	0.94
21.21	1,2-Dihydro-6-methyl-naphthalene	C <sub>11</sub> H <sub>12</sub>	3.98
21.84	o-Xylene	C <sub>8</sub> H <sub>10</sub>	1.45
21.99	Benzothiazole	C <sub>7</sub> H <sub>5</sub> NS	0.40
22.44	3,7,7-Trimethyl-1,3,5-cycloheptatriene	C <sub>10</sub> H <sub>14</sub>	1.91
23.04	4-Ethenyl-cyclohexene	C <sub>8</sub> H <sub>12</sub>	2.56
23.74	1,2,3-Trimethyl-benzene	C <sub>9</sub> H <sub>12</sub>	7.50
24.89	1,4-Dimethylbenzene	C <sub>8</sub> H <sub>10</sub>	7.31
25.22	2-Pyrrolidinone	C <sub>4</sub> H <sub>7</sub> NO	2.40
25.80	2-Methoxy-6-methyl-4H-pyran-4-one	C <sub>7</sub> H <sub>8</sub> O <sub>3</sub>	0.80
26.10	3-Methylene-4-(1,2-propadienyl)-cyclohexene	C <sub>10</sub> H <sub>12</sub>	1.72
26.71	2-Methyl-2-cyclopenten-1-one	C <sub>6</sub> H <sub>8</sub> O	0.88
27.14	Acetamide	C <sub>2</sub> H <sub>5</sub> NO	3.51
27.77	1-Acetylpyrrolidine	C <sub>7</sub> H <sub>11</sub> NO <sub>3</sub>	1.18
28.00	5,6-Dihydro-6-methyluracil	C <sub>5</sub> H <sub>8</sub> N <sub>2</sub> O <sub>2</sub>	2.12
28.95	Picolinamide	C <sub>6</sub> H <sub>6</sub> N <sub>2</sub> O	1.37
29.11	1-Ethynyl-1-cyclohexene	C <sub>8</sub> H <sub>10</sub>	2.22
29.38	Cyclohexene	C <sub>6</sub> H <sub>10</sub>	1.14
30.10	Hexahydropyrrolo [1,2- a] pyrazine-1,4-dione	C <sub>7</sub> H <sub>10</sub> N <sub>2</sub> O <sub>2</sub>	1.73
30.25	Methylstyrene	C <sub>9</sub> H <sub>10</sub>	0.68
31.22	1-Ethynyl-1-cyclohexene	C <sub>8</sub> H <sub>10</sub>	2.11
31.94	1-Isopropenyl-4-methyl-1,3-cyclohexadiene	C <sub>10</sub> H <sub>14</sub>	4.77
32.47	Tetramethylbenzenes	C <sub>10</sub> H <sub>14</sub>	0.23
33.14	1-Methylnaphthalene	C <sub>11</sub> H <sub>10</sub>	3.16

Abnisa and Daud [51] showed a maximum oil yield of 47.2, 47, 44, and 48.1 wt% during the copyrolysis of wood, pine nut shells, wheat straw, and palm shells combined with waste tyres. In all the above experiments, the yield of oil has increased with the addition of tyres. However, the trend found in this investigation is the contrary, which gives lower oil output with the addition of tyres with biomass. This is due to the higher yield of maximum initial oil production from castor seed oil cake compared to other biomasses.

### 3.5. Oil Characterization

**3.5.1. Physical Analysis.** Table 2 displays the various properties of the copyrolysis oil. The table shows that the oil has a higher amount of carbon and hydrogen with reduced

nitrogen and sulphur. The presence of oxygen is the fundamental factor that distinguishes biooils from hydrocarbon fuels. The oxygen content of the oil is 10.67 wt%, which is very low compared to other biomass pyrolysis oil [52]. The higher oxygen content in the biooil reduces the heating value of the oil, and it may corrode the engine parts while it is used as fuel for heating applications. The density of the derived oil is greater than the conventional diesel, and the viscosity is found to be nearly equal to the diesel fuel [53]. The heating value was estimated at 38.72 MJ/kg. From this, it can be implicit that the oil can be used as a fuel for furnaces and boilers.<sup>§</sup>Obtained at 50C : 50 T. <sup>§</sup>By difference.

**3.5.2. FT-IR Analysis.** The FT-IR analysis of the oil showed numerous peaks at various wavenumbers pertaining to

various functional groups (Figure 4). The various functional groups in the oil are ascribed to the different structures of the biomass and tyre material. During reaction, the waste tyres play a significant role as a hydrogen donor [54]. Alkanes, aliphatic, and aromatic compounds are the major elements present in the oil. The O-H stretching vibration at  $2925.38\text{ cm}^{-1}$  represents the existence of alcohols in the oil. The presence of alkanes is represented by the C-H stretching vibration at  $2925.38\text{ cm}^{-1}$ . The C=C stretching vibration at  $1627.94\text{ cm}^{-1}$ ,  $1497.68\text{ cm}^{-1}$ , and  $1389.95\text{ cm}^{-1}$  represents the availability of an alkane group in the oil. The C-O stretching and O-H bending at  $995.24\text{ cm}^{-1}$  represents the presence of alcohols and phenols. The C-H bending at  $771.75\text{ cm}^{-1}$  shows the occurrence of aromatic compounds in the oil.

**3.5.3. GC-MS Analysis.** This analysis also showed that the copyrolysis oil contained a variety of aliphatic and aromatic compounds with considerable phenolic compounds. The existence of phenolic and its derivatives was identified due to the decomposition of lignin in the samples. Benzene and its derivatives were also present more in the oil. Previously, pyrolysis of scrap tyres has revealed similar chemical compounds, which have been ascribed to the breakdown of rubber [55]. The chemical elements in the oil samples are traced using the NIST library and are listed in Table 3 with increased retention time. The oil's stability is improved by the reduced oxygenated components in tyre pyrolysis oil. D-Limonene, 1,2,3-trimethyl-benzene, 1,4-dimethylbenzene, 1-isopropenyl-4-methyl-1,3-cyclohexadiene, and acetic acid are available majority in the sample.

## 4. Conclusion

Copyrolysis of castor seed oil cake and waste tyres under different mass ratios was performed to understand the synergistic effect for maximum oil production. During the pyrolysis process, the biomass interacted with waste tyres and impacted the oil yield and quality. The product distribution is different at different feedstock ratios. The copyrolysis experiment showed maximum synergy on oil yield. Compared to the prediction, the copyrolysis process at a 50:50 blend ratio yielded 5.84% more oil products. The physiochemical characteristics of the oil obtained at the maximum synergistic effect were done to understand its basic compositions. The oil showed a maximum heating value of  $38.72\text{ MJ/kg}$ , which is better to be used as a heating fuel for a furnace. The chromatographic study showed that oil is a combination of different aliphatic and aromatic compounds with considerable phenolic compounds. The identified chemical compounds are used as feedstock for various chemical industries.

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that there are no conflicts of interest.

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