



OPEN Co-pyrolysis of furniture wood with mixed plastics and waste tyres: assessment of synergistic effect on biofuel yield and product characterization under different blend ratio

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Pyrolysis of waste furniture wood, mixed plastics and waste tyres was examined separately and in different combinations from the perspective of improved value products and energy production. The effect of different combinations of furniture wood, plastics and tyres on the product distribution during co-pyrolysis was analyzed. The experimental work throughout this study was performed at a temperature of 500 °C. Prior to the pyrolysis experiments, thermogravimetric analysis was done to assess the thermal degradation behavior of all selected feedstocks. During individual pyrolysis, mixed plastic wastes produced 70.6 wt% of pyrolysis liquid, which is 37.9% and 33.4% more than furniture wood and waste tyres. During co-pyrolysis, a binary blend of mixed plastics and waste tyres produced 63.3 wt% of pyrolysis liquid, which is 7.65% more than the logarithmic mean value, indicating a positive synergistic interaction on liquid production. The liquid yield of the ternary blend was observed to be as low as 54.4 wt% due to the lower volatiles present in the blend. The presence of volatiles in the feedstock is correlated with the production of liquids by individual and co-pyrolysis. For feed-flexible, more efficient, and cleaner operating systems, the increased liquid production offers crucial information. With the use of Fourier transform infrared spectroscopy (FT-IR) and gas chromatography/mass spectroscopy (GC-MS), the impact of different combinations on product characterization was investigated. The characterization study of the pyrolysis liquid obtained from mixed plastics showed the presence of different aromatic and aliphatic compounds. The findings offered viable options for efficiently utilizing waste materials, particularly plastics and tyres to improve the quality and substance of products.

Keywords Co-pyrolysis, Binary and ternary blends, Synergistic effect, Characterization

The use of fossil fuels is still very high throughout the world. The combustion of fossil fuels results in about 70% of greenhouse gas emissions. Over 37 billion tons of carbon dioxide (CO₂) from fossil fuels were emitted globally in 2023, surpassing the 40 billion-ton threshold. In line with a 10-year plateau, overall emissions are up 1.1% from 2022 levels and 1.5% from pre-pandemic levels¹. In general, burning fossil fuels emits 70% of

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total global greenhouse gas emissions and there are two possible ways to reduce CO₂ emissions, such as leaving fossil fuel usage in the ground and using carbon capture technologies. A portion of the necessary decreases in fossil fuel emissions could be offset by negative emissions from direct air capture, afforestation and bioenergy. However, there are a lot of unknowns surrounding these possibilities in terms of their potential costs and level of contribution². In order to reduce these adverse effects on the environment, finding and utilizing alternative renewable energy is essential for the present condition. The use of waste as a source of fuel (recovery of energy) has expanded in recent years due to a number of factors. Other than the depletion of fossil fuels, some of the most crucial problems facing our civilization today are waste management, climate change, environmental degradation, human health, and the depletion of fossil fuels.

Hazardous chemicals are released into the atmosphere during the burning of plastics and tyres, polluting the surrounding area and ecosystem. Polychlorinated biphenyls, furans, dioxins, and mercury are the most harmful gases released when plastics are burned³. The constant demand for plastics resulted in an accumulation of plastic garbage in landfills, taking up a lot of space and contributing to the environmental problem⁴. Global plastic production stretched to 348 MT in 2017, and by 2050, it is predicted that demand will have quadrupled⁵. Prior to 1980, all the used plastics were dumped and the amount raised at the rate of 0.7% per year⁶. Every year huge amount plastics are burned and dumped into the earth surface. The rate of incineration would rise to 50%, recycling to 44%, and trash to 6% if historical trends were inferred through to 2050⁷. Recycling is seen as another option for handling plastic trash to decrease landfilling. Due to the limitations on water pollution and insufficient separation skills, recycling plastic has proven to be challenging and expensive⁸.

The reduction of conventional fuels, pollution and demand for energy are the three major issues facing the globe due to the continuous development of the population and industrialization. Due to these challenges, it is essential to develop renewable energy sources through thermochemical conversion methods like pyrolysis. Pyrolysis is a thermal degradation process that uses heat to break long polymers into smaller compounds without the presence of oxygen or air. Many researchers have worked on the pyrolysis of waste plastics to generate high quality liquid fuels up to 80 wt%^{9–11}. At the same time, the liquid products obtained through pyrolysis don't need to be upgraded or treated for heating applications¹². Numerous researchers have conducted surveys on the pyrolysis of various plastics and the production of pyrolysis liquid. From the survey, it can be noted that the reaction parameters have a considerable impact on product yield and its quality¹³. Prior to pyrolysis, the waste plastics must be thoroughly characterized because these wastes may contain a variety of hazardous compounds, including halogens and other detrimental additives¹⁴. These hazardous elements could possibly escape from the reactor system and pose major threats to the environment and public health. So while pyrolyzing plastic waste, it is highly advised to take a complete risk assessment to identify all potential hazards associated with the process and to develop effective mitigation techniques. Polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyethylene (PE), polystyrene (PS) and polypropylene (PP) are the most widely used commodity plastics. The feedstock used for pyrolysis studies determines the production of the product. Waste PVC was pyrolyzed by Miranda et al.¹⁵ at temperatures ranging between 225 and 520 °C. Under vacuum conditions, the amount of liquid oil was produced from 0.5 wt% to 13.0 wt%. The survey recently conducted by Sharuddin et al.² showed that the PVC is not appropriate for pyrolysis, since it produces a lesser quantity of liquid oil. Additionally, the amount of PVC in municipal waste is less than 3% compared to other plastic waste. PET has emerged as a good choice for the packing of food items, mineral water and soft drinks. Liu et al.¹⁶ recovered energy rich biofuel from waste PET using microwave pyrolysis. Instead of pellets, the authors utilized thin sheets of PET with an average size of 10 × 10 mm². The study illustrated that increasing the sheet size increased the overall efficiency of the process. The study produced 40 wt% of char and 34.38 wt% of gas at 550 °C. Dhahak et al.¹⁷ conducted pyrolysis on PET at temperatures between 410 and 480 °C. In this study, a maximum benzoic acid of about 11 wt% was attained at 430 °C. The applications of PE for diverse purposes contribute roughly 17.6% of the total plastic waste category in municipal waste. PE is a suitable feedstock since it produces the maximum liquid oil. Pyrolysis of high density polyethylene (HDPE) in a micro steel reactor produced a maximum of 80.8 wt% liquid. The study discovered that the pyrolysis liquid is the major product rather than solid and gas and had the maximum total conversion at 350 °C¹⁸.

Due to the rapid development of automotive industries, for the past decade, millions of waste tyres have been dumped, buried and disposed of, which poses a severe threat to the atmosphere and eco systems. It is assessed that the number of waste tyres would reach to 5000 million by the year 2030 and it should be disposed in a proper way¹⁹. The higher energy level of waste tyre is directly used as a combustible material for paper and cement industries²⁰. However, the harmful pollutants produced during the combustion of scrap tyres are a hindrance, with higher dioxins. The waste tyres collected from heavy trucks are processed efficiently to produce recycled rubber and retreaded tyres. But the tyres from small cars are not processing effectively and are damage to the eco system²¹. Due to the ecological considerations, it is clear that the disposal of waste tyres is focused more on high-value applications than reducing their quantity²². In this background, pyrolysis is considered as a significant option for treating waste tyres²³. There are numerous studies are available on the production of oil and gas by tyre pyrolysis. Previously, waste tyres were pyrolyzed by Czajczyńska et al.²⁴ at 400, 500, and 600 °C and the products were examined in relation to their effects on the environment. Heavy metal concentrations in pyrolysis oils and chars were quite low, making them suitable for use for the environment and people's health. The authors suggested that pyrolysis of waste Tyres is more profitable due to the presence of desirable compounds. Khudhair et al.²⁵ prepared pyrolysis liquid using waste tyres through conventional and catalytic pyrolysis. The authors examined both the liquid products and found a mixture of various hydrocarbons such as paraffins, isoparaffins and aromatics. Yasar et al.²⁶ assessed the quality and environmental impacts of pyrolysis liquid obtained from waste tyres. Passenger tyres were pyrolyzed by Aslan et al.²⁷ at temperatures of 30–600 °C. They came to the conclusion that the heating rate can significantly affect the degradation of the material. However, before doing tyre pyrolysis process, like plastic pyrolysis, their safety needs to be thoroughly examined. The

use of pyrolysis products is hindered by the comparatively high sulfur content of tyres²⁸. During the rubber vulcanization process, sulfur is added to tyres to improve their toughness and resist heat. Although the amount of sulfur from tires varies in the pyrolysis products, it remains in the pyrolysis products. Particularly, compounds with a gaseous sulfur concentration are hazardous.

Co-pyrolysis of biomass with mixed plastics and tyres is a possible approach to get energy-rich pyrolysis liquid and it can be used for fossil fuel alternatives²⁹. Co-pyrolysis of waste biobased materials, plastics and tyres enhances the production of hydrogen-rich gaseous and oil products through synergistic interactions. Numerous studies have verified that the quantity of the yield was increased by co-pyrolysis technique without altering the process parameters. Vibhakar et al.³⁰ conducted co-pyrolysis experiments on mixed agricultural residues and mixed plastics. In this study, the authors used different agricultural residues. The co-pyrolysis experiment at the combination of 40% biomass with 60% plastics yielded a maximum liquid product of 60.42 wt%. Like the previous experiment, the co-pyrolysis of neem wood bark and LDPE conducted by Kaushik et al.³¹ showed a maximum positive synergy on pyrolysis liquid yield at 40% neem bark with 60% LDPE. Many literatures have also conducted co-pyrolysis experiments on biomass and waste tyres. Martínez et al.³² conducted co-pyrolysis of forestry wastes and waste tyres. There was evidence of beneficial interactions among tyre particles and biomass due to positive synergistic. The co-pyrolysis liquid had a higher pH and improved calorific value with decreased acidity and moisture content compared to raw biomass bio-oil. Chen et al.³³ used a thermogravimetric study to determine the pyrolysis behaviour of tobacco stalk and scrap tyre on gas yield. The kinetic analyses of the study demonstrated that Arrhenius law and first-order reactions provide a systematic explanation for the weight loss subintervals discovered for both the materials and their blends. During the pyrolysis of agricultural wastes and tyres, Khan et al.³⁴ noted significant synergistic interactions. With the addition of waste tyres to rice straw, the authors produced pyrolysis liquid with decreased oxygenated chemicals and a significant increase in aromatic and aliphatic hydrocarbons. Wood from waste furniture is also considered as biomass and utilized for pyrolysis experiments^{35–37}. Heo et al.³⁵ conducted fast pyrolysis experiments of waste furniture wood under different operating conditions for maximum bio-oil production. Through experimental results, it was noted that at 450 °C, the process produced a maximum of 65 wt% bio-oil. In another study, Moreno et al.³⁶ aimed to produce gaseous products. The authors produced maximum gas fractions at the optimum temperature of 360 °C.

The objective of this study is to co-pyrolyze waste furniture wood along with mixed plastics and waste tyres. The selected feedstocks for the production of biofuel are a crucial component of sustainable waste management. Biofuel yields are impacted by the quality and organic substances present in the feedstocks. The feedstocks were obtained at no cost. The feedstocks were pyrolyzed at different ratios at the temperatures of 500 °C, since the maximum liquid product was observed at this condition. This work is novel by considering the selection of feed materials and their combination for the co-pyrolysis process. To the knowledge of the authors, no work has been reported with the combination of biomass, plastics and tyres. Analysis was done on a fixed bed reactor to find the effect of material blend on the distribution of the products. Analytical methods like Fourier transform-infrared spectroscopy (FT-IR) and gas chromatography-mass spectroscopy (GC-MS) were used to characterize the pyrolysis liquid and the physicochemical parameters were assessed in accordance with ASTM standards.

Methodology

Materials and methods

Waste furniture wood particles, mixed plastics and waste tyres are the raw materials used for this study. The raw materials like waste plastic, waste tyres are gathered from Saveetha Industries, Chennai, Tamil Nadu, India, were utilized in this research. It is said that no samples taken from the wild or from the agricultural lands by considering the national or worldwide concern. Every procedure was carried out in compliance with the applicable national and international norms, legislation, and recommendation. In the move to a closed plastic loop and the circular economy, plastic recycling is encouraged, usually through mass-based recycling objectives. The waste plastics collected from domestic and industrial sectors are contaminated and heterogeneous. These types have a limited number of applications because of their lower quality. Globally, the furniture industry produces huge amounts of waste fiber. Furniture wood has no conventional pathway for reuse due to its organic elements, and disposing of it causes serious environmental issues. Waste tyres make up an important portion of the overall solid waste stream in terms of tons. The End of Life Vehicle Directive, which mandates the separation of waste tyres from vehicle and promotes tyre recycling. Furthermore, the disposal of waste tyres in landfills is prohibited. The pathways for treating waste tyres have been significantly altered by various initiatives. Using tyres as fuel in cement kilns is one of the primary methods for handling discarded tyres. Tyres can also be recovered energy-wise by being used in power plants or co-incinerating with other waste. In many parts of south India, waste furniture wood and tyres are utilized for cottage industries as fuel. Open burning of these wastes pollutes the environment and affects human health. These wastes can be treated and used as a source of raw materials or alternative fuels by using them for pyrolysis. Furniture wood particles contain adhesives and paints applied during manufacturing. The maximum portions of the paint and varnish were removed before processing. The solid wood was cut into small pieces and further converted into a pellet of 0.5 mm diameter. The plastic material used for the analysis is a mixture of all types of polymers. The plastics were also cut into small pieces to get the size of 0.5 mm. The waste tyres used for this study were manually separated from their steel frames and cut into small pieces. The fabric cords provided in the tyres were also separated before conducting the experiments. The initial process starts with cleaning and separating the material from sand, metal pieces and other solid impurities. All the samples were dried in an oven for two hours. Proximate and ultimate analysis of the feedstocks was conducted based on ASTM standards. The primary characteristics of all individual feedstock are displayed in Table 1. When applied in the early stages of research, life cycle assessment (LCA) has the potential to significantly influence the development of products and methods with enhanced environmental credentials³⁸. In terms of their ability to contribute to global warming, LCA studies have shown that pyrolysis of waste plastics and tyres is a better environmental

Content in (wt%)	Furniture wood	Mixed plastics	Waste tyres
Proximate analysis			
VM	68.5	95.1	63.4
FC	20.3	0.4	25.5
MC	9.3	0.8	1.1
A	1.9	3.7	10.0
Ultimate analysis (ash free basis)			
C	48.22	79.63	80.01
H	6.03	14.97	8.92
N	1.28	2.70	0.54
S	0.14	0.31	1.73
O	44.32	2.39	8.80

Table 1. Properties of feedstocks in wt% % of O = 100 – (C + H + N + S) %

Type of pyrolysis	Blend type	Feed material
Individual pyrolysis	No blend	Furniture wood
		Mixed plastics
		Waste tyres
Co-pyrolysis	Binary blend	Furniture wood + Mixed plastics
		Furniture wood + Waste tyres
		Mixed plastics + Waste tyres
	Ternary blend	Furniture wood + Mixed plastics + Waste tyres

Table 2. Experimental scheme.

alternative than landfilling or incineration³⁹. The process also has positive effects on the environment in terms of potential ecotoxicity, climate change, fossil fuel depletion and human toxicity. Pyrolysis of plastics and tyres reduces the amount of waste that would need to be disposed of, enhances environmental sustainability and reduces the need for fossil fuels.

Reactor set up and procedure

The technical details of the reactor set up used for this study have already been reported in the literature³⁷ and are further elucidated in this section. The fixed bed reactor is cylindrical in shape with an internal diameter of 100 mm. The reactor was designed with top feeding mechanisms. For heating, an electrical resistance heater is surrounded by the reactor. A PID controller with two K-type thermocouples was attached to the reactor to control the temperature. The condenser unit is connected to the reactor's exit to condense the volatiles. Safety during the pyrolysis of plastics and tyres is more crucial. Failure during the pyrolysis process affects the recycling schedule and the economic benefits of the project. The experiments in this study were conducted with many safety measures. The combustion sources were turned off until the end of the experiment. The gas and condenser pipes were checked prior to the experiment in order to avoid condensable and non-condensable gas fractions. The experiments were carried out at three different phases. For each experiment, the reactor was cleaned and the trash from the previous experiment was removed. For each run, 90 g of feedstock were kept inside the reactor. Up to 90 g of samples were loaded and pyrolyzed at 500 °C. The reason why the pyrolysis experiments were conducted at 500 °C can be attributed to the decomposition behavior of the selected feedstocks. In general, the breakdown of biomass starts at 250 °C. But the fraction of lignin starts around 420 °C. The TGA analysis of the feedstock also showed the maximum decomposition of the material around 500 °C. So it can be identified that the synergistic effect is greater during the reaction conducted at 500 °C since the decomposition range of wood, plastics and tyres is similar. At first, the yield characteristics of the individual feedstocks were recorded. For co-pyrolysis experiments, binary and ternary blends were prepared. For a binary blend, the materials were mixed at 1:1 ratio (45 + 45 g). For ternary blends, the materials were mixed at a mass ratio of 30 + 30 + 30 g. For all the experiments, the reactor is held for 45 min at final temperature. The experimental scheme planned for this study is displayed in Table 2. The liquid oil obtained from individual and co-pyrolysis experiments is weighed and kept for characterization studies. The pyrolysis characteristics were assessed by measuring the yield quantity. The char is collected separately and weighed. In order to assess the repeatability of the experimental yield, each test was carried out three times under identical operating conditions. Figure 1 shows the overall methodology flow chart for this study.

Characterization study

Proximate and ultimate analysis of the selected feedstock were done for all the feedstocks. Proximate analysis provides the composition of the feedstock and hence it is comparatively simple to measure. For proximate

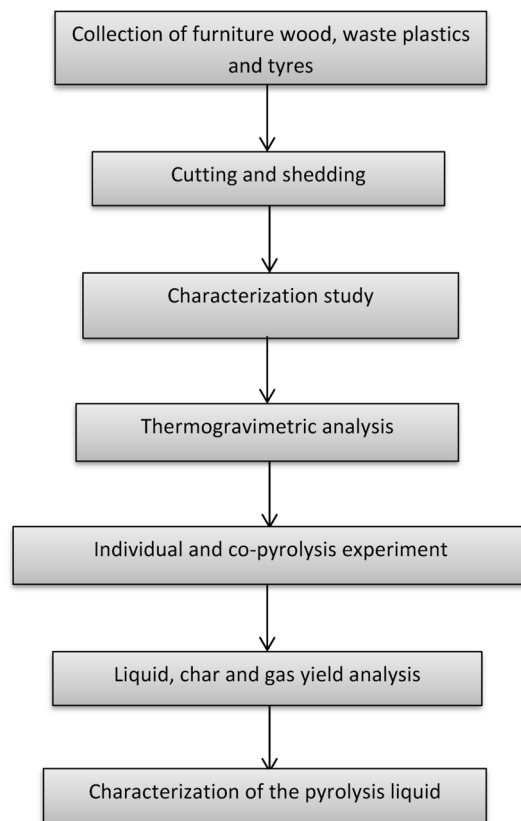


Fig. 1. Methodology flow chart.

analysis, the moisture content of the sample was found by the percentage weight loss method. In this analysis, a known weight of the sample is dried in an oven at 100 °C until a constant weight is reached. The ash content was also measured using percentage weight loss by incinerating the sample in a muffle furnace at 550 °C. The analysis was carried out by consuming 5 g of sample. A CHNS analyzer (Elementar Vario EL-III) was utilized for material component analysis. The analysis was carried out under ash free basis. The material was subjected to TGA analysis using a Thermal Analyzer (TGA701). The analyzer has a high-temperature thermal balance system, control system, air control system, data processing system, data acquisition system and system software. The maximum temperature for the analysis can be set to 1450 °C and the analyzer can hold up to 10 g of sample for the analysis. The heating rate for the analysis can be varied from 5 °C to 50 °C with a maximum carrier gas flow rate of 100 mL/min. For TGA, the material was heated up to 900 °C (at 20 °C/min). For TGA analysis 10 mg of the material was loaded into the furnace and the weight loss function related to the temperature was recorded. For this analysis nitrogen was admitted at the rate of 50 mL/min. With the help of a calorimeter (Parr-6772), the calorific value of the liquid was found. FTIR is a simple, quick, inexpensive, and non-destructive analytical method that has been effectively used to study the chemical composition of the pyrolysis liquid. The functional group of liquid was analyzed using a Bruker Tensor 27 FT-IR (Bruker Optik GmbH, Germany) spectrophotometer with DLaTGS detector. A thin film between KBr plates were used to perform the analysis. For this analysis, a self-supporting pellet was formed by carefully combining around 10 ml of the sample with 300 mg of dry KBr. In this analysis, infrared light interacts with the sample, which causes chemical bonds to expand, contract, and absorb infrared radiation within a certain wave length range. The spectra were obtained in triplicate in a random order with 24 scans with 4 cm⁻¹ resolution. For the entire analysis, OPUS TM software was used. The HP-5 capillary column (30 m × 0.25 mm × 0.25 mm) equipped Thermo MS DSQ II spectroscopy was used for the quantitative and qualitative measurement of the pyrolysis liquid under Helium environment. A 20:1 injector split ratio was used, and the injector temperature was fixed to 250 °C. In order to avoid any solid spill during the GC analysis, 0.1 mg of the liquid oil sample was kept in the cup and covered with quartz asbestos on both sides. The final temperature for the process was set to 650 °C and processed for 10 s. The GC column was configured with an initial temperature of 50 °C and maintained for 5 min. After that, the temperature was raised to 250 °C at a rate of 10 °C/min and maintained for 10 min. The MS spectra were identified by electron ionization at (70 eV) for 40–650 m/z range. Utilizing the NIST mass spectral database, chemical substances associated with each peak in bio-oil chromatograms were identified.

Modeling approaches

There has been a lot of research and development on creating mathematical models for understanding the process of pyrolysis in order to facilitate large-scale expansion in the biofuel production sector. In order to

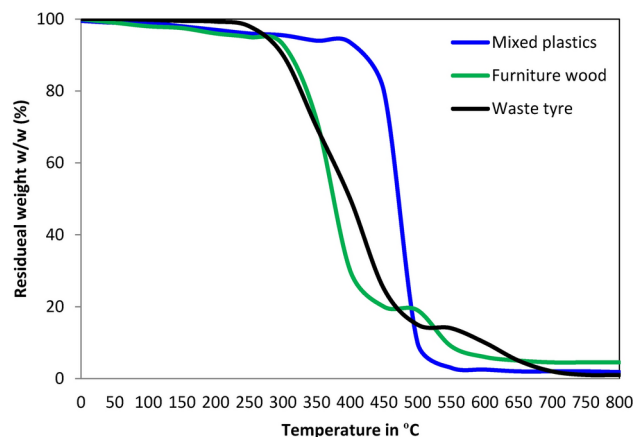


Fig. 2. TGA curve of the feedstock.

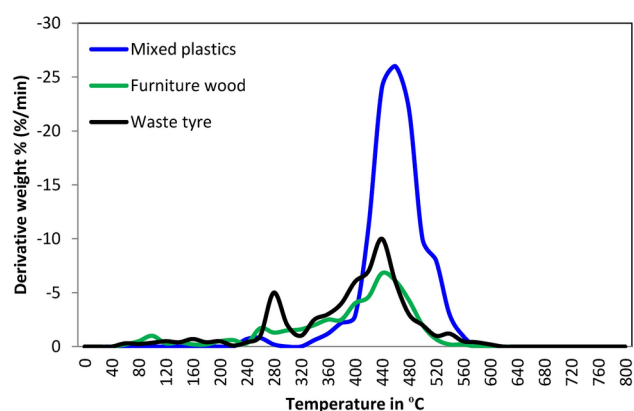


Fig. 3. DTG curve of the feedstock.

derive mathematical models and comprehend the intricate reaction chemistry of the process, chemical kinetics is more essential⁴⁰. The product yields are determined in a significant manner by heat and mass transfer models. An extensive modeling technique known as an artificial neural network (ANN) uses an extensive dispersion of basic processing components to provide an output of intricate processes involving discrete and nonlinear phenomena. ANN models are the most successful one for a wide range of applications. It is the most appropriate modeling tool for optimizing complicated system parameters. Madhu et al.⁴¹ conducted a pyrolysis experiment on cotton shell and optimized the process parameters for yielding maximum bio-oil yield using ANN. For their analysis, the previously acquired experimental readings were used as input. When the results of the ANN and experimental models were compared, they were almost identical. This shows the relationship between prediction and experimentation. When predicting the correlation between multivariant, nonlinear biomass and yields, feed-forward networks (FFN) and cascade-forward networks (CFN) are also taken into consideration in addition to ANN. In this work, no analytical work has been assigned to predict the product yield since there is limited experimental data.

Results and discussion

Thermogravimetric analysis

The TGA and DTG curves of the selected feedstock are shown in Figs. 2 and 3. Within the decomposition range, furniture wood had a higher mass loss compared to mixed plastics and waste tyres. Additionally, the DTG curve for furniture wood revealed a smaller peak than that of the other two materials, with maximum decomposition at 425 °C. The lower mass loss is the representation of lower volatiles (68.5 wt%) in the furniture wood. The adhesive materials found in the material also decomposed between 250 °C and 550 °C⁴². Given that the binding adhesives are thermally unstable, they decompose earlier than the lignocellulosic content. The cellulose and lignin in the wood samples started to break at 310 °C. For all the materials, initial mass loss was first noticed during the drying process and the majority of the volatile matters were released between 230 °C and 580 °C. For furniture wood, the devolatilization step contributed to almost 70% of the mass loss, indicating that the majority of volatiles were released as a result of the breakdown of lignocellulosic components. Hemicellulose, cellulose and lignin are the primary elements of lignocellulosic wood materials. These materials have diverse chemical structures that cause them to degrade at different temperatures⁴³. The remaining non-volatile carbon is carbonized during the final

breakdown stage to create biochar⁴⁴. Unlike biomass, mixed plastics are homogenous in structure, hence the mass loss occurs in a single stage at a higher temperature³⁰. It starts to degrade at 375 °C due to its long chain polymeric structure and completely degrades at 50 °C with very few residues. At temperatures between 400 and 500 °C, the plastic waste loses 97% of its mass, and no further disintegration was recorded after 500 °C. These results agree with other published data^{45,46}. The TGA of waste tyres shows that the degradation started at 235 °C. The tyre materials were degraded at two different stages; 250 °C to 310 °C and 310 °C to 515 °C. The first peak is caused by the degradation of oils, plasticizers and additives, while the next peak represents the breakdown of natural rubber, polybutadiene and polybutadiene-styrene⁴⁷. Senneca et al.⁴⁸ also suggested that the second peak also belongs to the degradation of rubbers and the remainder.

Individual pyrolysis characteristics

Figure 4 displays the yield of pyrolysis products during individual pyrolysis of furniture wood, mixed plastics and waste tyres. The pyrolysis experiments were conducted by keeping the reactor at 500 °C. The conversion and yield of the products are knowingly prejudiced by the bed temperature⁴⁹. The temperature below 300 °C recommended for the development of higher char due to improper heat transfer and volatilization. On the other hand, higher bed temperatures favour the development of higher gas fractions. During biomass pyrolysis, at a temperature between 100 °C and 200 °C pre pyrolysis of biomass takes place. In this phase, moisture is evaporated and its bonds are broken, which creates free radicals. At temperatures below 100 °C, cellulose starts to decompose and this process is distinguished by a reduction in polymerization. The primary factor leading to the generation of the highest liquid yield is the breakdown of cellulose and hemicellulose, which occurs between 200 °C to 350 °C⁵⁰. The higher molecular disruption is caused by the significant breakdown of biomass at higher heat inputs, which also yields a range of chemical elements. Based on the reports^{51–53}, when the bed is maintained at around 500 °C, substantial transformation of biomass, plastics and tyres to liquid occurs. In individual pyrolysis, furniture wood yielded a maximum of 43.8 wt% liquid products, which is very low compared to the yield obtained from mixed plastics (70.6 wt%) and waste tyres (47.0 wt%). The higher output of liquid products with mixed plastics could be attributed to the increase in volatile materials. Compared to furniture wood and waste tyres, the volatile matter of the mixed plastics is as high as 95.1 wt%. According to the recent study reported by Madhu et al.⁵⁴, volatile matter is the key element for the conversion of pyrolysis liquid. According to the proximate analysis reported in Table 1, mixed plastics had a higher fraction of volatiles (95.1 wt%) compared to waste tyres (63.4 wt%) and furniture wood (68.5 wt%). Furthermore, there is an excellent correlation between the feedstock's ash and pyrolysis liquid output. In general, the ash in the feedstock promotes the formation of char. The amount of char production was highest for waste tyres (38.1 wt%) due to its greater ash content. The production of non-condensable gas is 28.9 wt%, 25.0 wt% and 14.9 wt% for furniture wood, mixed plastics and waste tyres, respectively.

Co-pyrolysis of binary blend

The yields of the co-pyrolysis process with binary blends are illustrated in Fig. 5. During co-pyrolysis of binary blends, a maximum liquid production of 63.3 wt% is obtained from mixed plastics and waste tyres. Compared to the theoretical yield, this combination produced 7.65% more liquid. But for gas and char, there is some negative synergy that was recorded. When mixed plastics and waste tyres were pyrolyzed individually, they produced 70.6 wt% and 47 wt% of pyrolysis liquid, respectively. But the combination of these two materials produced more than the arithmetic mean of the individual pyrolysis liquid. The co-pyrolysis of furniture wood and mixed plastics produced little more than the arithmetic mean of their individual values. Compared to the theoretical value, it produced 2.1% more liquid. At this combination, the total gas and char obtained is almost same as the arithmetic mean of the gas and char obtained through individual pyrolysis. The combination of furniture wood and waste tyres produced a lower yield of liquid products than other combinations. The co-pyrolysis of furniture wood and waste tyres produced 45.1 wt% of pyrolysis liquid, this is almost equal to the arithmetic value

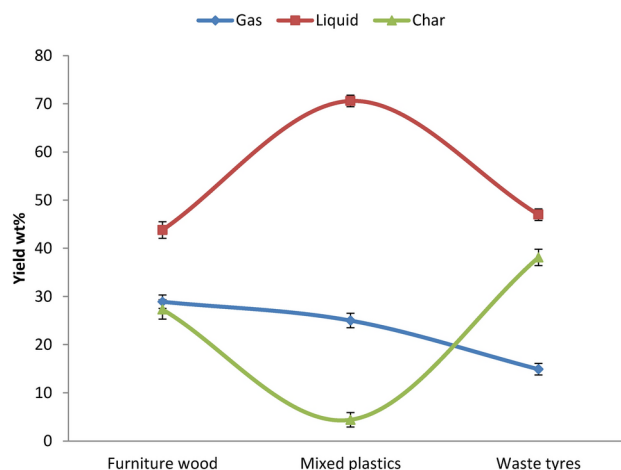


Fig. 4. Product yield of individual pyrolysis.

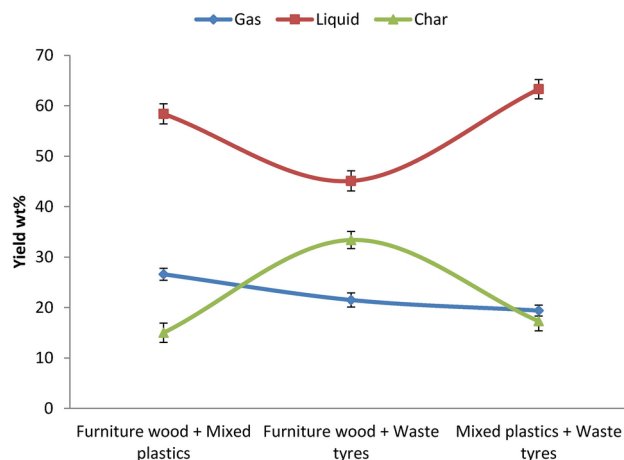


Fig. 5. Product yield of co-pyrolysis of binary blend.

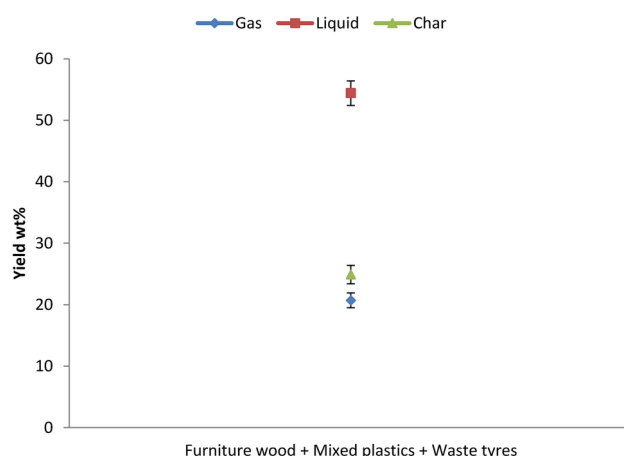


Fig. 6. Yield of co-pyrolysis of ternary blend.

of individual pyrolysis liquid. The char and gas yield are also the same as the arithmetic mean value. The total volatile matter in the feedstock determines the yield of pyrolysis liquid at various feedstock combinations. More liquid products were produced by the mixture of waste tyres and mixed plastics due to the higher volatile matter content. According to Johannes et al.⁵⁵ the radical interactions is key phenomena for the synergistic effects which is determined by the combination of the feedstock. From the previous study, it is also clear that the blending of feed material is also a significant factor that affects the yield⁵⁶.

Co-pyrolysis of ternary blend

The product yields of the co-pyrolysis process with ternary blends are illustrated in Fig. 6. In this phase of the experimental work, the liquid product yield is low than binary blends. The weight percentage of the liquid oil through individual pyrolysis was 43.8 wt%, 70.6 wt% and 47.0 wt% for furniture wood, mixed plastics and waste tyres, respectively. But the ternary blend produced 54.4 wt% of liquid products, which is little more than the arithmetic mean of the individual pyrolysis yield. Compared to the theoretical yield, the experiment produced 1.12% more liquid and 7.33% more char products. The result showed positive synergy on liquid and char yield. The yield of gas was decreased by 8.0% compared to individual pyrolysis. The volatile material in the combined material is the key factor for higher liquid products⁵⁷. It is also confirmed that the lower volatile matter in the ternary blend (75.8 wt%) than binary blend (79.5 wt% with mixed plastics + waste tyres) yielded lower liquid products. The higher gas fractions from the ternary blend can be explained by the catalytic effect of ash which promote the production of gas products by breaking condensable volatiles.

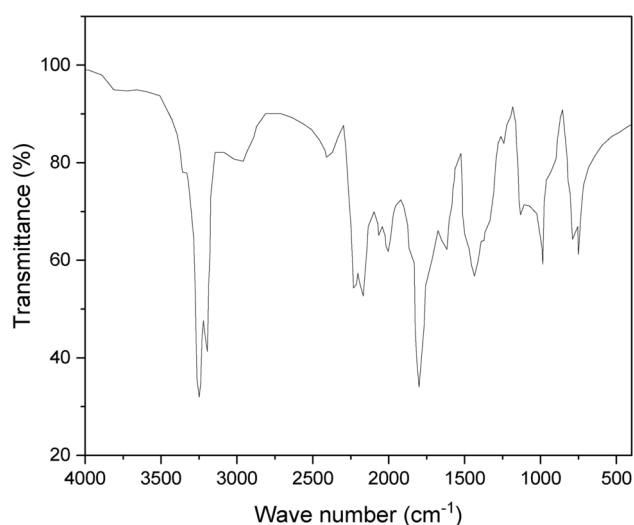
Heating value analysis

The pyrolysis liquid obtained at maximum quantity through each phase was considered for heating value analysis and reported in Table 3. With a higher heating value (44.08 MJ/kg), the liquid produced from mixed plastics is more efficient. The liquid made from the ternary blend of furniture wood, mixed plastics and waste tyres has a lower heating value (32.54 MJ/kg) because it contains considerable oxygen content with less volatile⁵⁸. For usage

Feedstock	Yield quantity (wt%)	Heating value (MJ/kg)
Mixed plastics	70.6	44.08
Mixed plastics + Waste tyres	63.3	41.71
Furniture wood + Mixed plastics + Waste tyres	54.4	32.54

Table 3. Heating value analysis.

Material	Density (kg/m ³)	Viscosity (cSt)	Flash point (°C)	Fire point (°C)	pH	HHV (MJ/kg)
Mixed plastics*	865	2.74	64	69	3.7	44.08
Mixed plastics + Waste tyres*	905	2.71	67	72	3.2	41.71
Furniture wood + Mixed plastics + Waste tyres*	960	3.64	105	115	3.3	32.54
Plum seed ⁵⁹	940	1.14	112	#	3.19	22.39
Municipal plastic ⁶⁰	835	2.52	42	45	#	44.34
Waste tyres ⁶¹	942	3.5	69	95	#	41.50
Cotton shell ⁶²	1005	7.8	160	#	3.3	18.35
Napier grass ⁶³	1274	2.32	#	#	2.3	19.79
Diesel ⁶⁴	840	2.61	58	63	#	42.80

Table 4. Comparison of physical properties of pyrolysis oil. *This study, #Not reported.**Fig. 7.** FT-IR analysis.

as a low-energy fuel, pyrolysis liquid with minimum calorific value of 20 MJ/kg is advised. The pyrolysis liquid, with lower heating value, can be used for a variety of chemical treatments. In addition to the heating value, some important physical characteristics of the pyrolysis liquid are given in Table 4. The table compared the values with some other pyrolysis oils derived from different feedstocks and diesel. Among the pyrolysis liquid combinations of furniture wood, mixed plastics and waste tyres has a higher viscosity of 3.64 cSt. The flash point of the liquid was also high, at 105 °C. The higher viscosity of the liquid makes it easier to store at normal atmospheric temperatures. Compared to diesel fuel, pyrolysis oil has higher flash and fire points. The higher heating value of the mixed plastic oil compared to diesel and other pyrolysis oils favors the utilization of heating fuel for furnaces.

Chemical analysis

The pyrolysis liquid made from mixed plastics is considered for chemical analysis since it is more efficient and produced more than other feedstock. The chemical characterization analysis was done with the help of FT-IR and GC-MS.

FT-IR analysis

The FT-IR spectrum of the pyrolysis liquid is illustrated in Fig. 7. The result implies that in the $\equiv\text{C-H}$ bend at 3245.4 cm^{-1} , the existence of alkynes is possible. The O-H stretch at 3220.1 cm^{-1} indicates the presence of

carboxylic acids. The presence of alkanes and alkyls is possible due to the existence of C-H bend at 3016.0 cm^{-1} . The $\text{C}\equiv\text{N}$ stretch visible at 2232.2 cm^{-1} denotes the presence of nitriles. The existence of acyl chlorides confirmed by identifying $\text{C}=\text{O}$ symmetric at 1800.5 cm^{-1} . The carboxylic acids were identified by the $\text{C}=\text{O}$ stretch obtained at 1675.9 cm^{-1} . The ring $\text{C}=\text{C}$ stretch and C-H bend identified at 1454.4 cm^{-1} and 789.3 cm^{-1} show the existence of aromatic compounds.

GC-MS analysis

For the purpose of analyzing the chemical compounds appeared during the decomposition of the mixed plastics, mass spectrometry was also used to analyze the liquid fractions. Only chemical compounds with a similarity index of more than 90% are reported in this analysis. Table 5 displays the existence of several chemical components identified in the liquid. The table indicates higher concentration of C_9H_8 , C_7H_{12} , $\text{C}_{14}\text{H}_{30}$, C_9H_{18} and $\text{C}_{11}\text{H}_{22}$. Their area percentages are 10.11, 8.76, 4.55, 4.47 and 3.77 respectively. Similar compounds were also identified and reported by Yan et al.⁶⁵, Adrados et al.⁶⁶ and Vibhakar et al.³⁰. The degradation of plastic materials produced the majority of aromatics and aliphatics. The PET in the plastic material produced some oxygenated elements⁶⁷. The appearance of nitrogen and sulfur-containing elements is the result of the contaminants in the feed materials such as colouring agents, adhesives and sands etc.⁶⁸. 2,4-Dimethyl-1-heptene identified in this analysis belongs to an alkene and is a volatile organic compound. It derives from the hydride of a heptane. Azulene identified in this study has an area percentage of 10.11. It is an aromatic organic compound and an isomer of naphthalene. It is a dark blue compound. 2,4-Dimethyl-1,3-pentadiene has been used to study the structure of its various conformational isomers and their vibrational spectra⁶⁹. Phenol, 2,4-dimethylphenol existing in the pyrolysis liquid, is a combustible solid or liquid. It can be ignited by static discharge or sparks. 2,4-dimethylphenol appears as colorless crystals or a clear, dark amber liquid. It can be used to make phenolic antioxidants, pharmaceuticals, plastics, resins and solvents. It is also used for the production of disinfectants, bactericide, germicides, and sanitizers. 2-Methylnaphthalene is a polycyclic aromatic hydrocarbon (PAHs). Over 20% of the carbon in the world may be related to PAHs, possible preparatory materials for the development of life. 1,3,5-trimethylcyclohexane is a highly flammable liquid and vapor. It has a molecular weight of 126.24 g/mol. Tetradecane appeared in the liquid oil, is generally called N-Tetradecane. It is a colorless liquid and must be

RT/min	Name	Formula	Area %
3.71	2,4-Dimethyl-1-heptene	C_9H_{18}	3.74
3.92	3-Methyl-1-phenyl-1H-indene	$\text{C}_{16}\text{H}_{14}$	2.41
5.01	Dibenzo[a,e]cyclooctene	$\text{C}_{16}\text{H}_{12}$	3.94
5.85	1,3-Pentadiene, 2,4- dimethyl	C_7H_{12}	8.76
6.77	1-Ethyl-1,2,3,4-tetrahydrocarboline	$\text{C}_{13}\text{H}_{12}\text{N}_2$	2.99
9.11	Azulene	C_9H_8	10.11
10.26	Pyrene, 1-methyl-	$\text{C}_{17}\text{H}_{12}$	0.33
10.55	Tetradecane	$\text{C}_{14}\text{H}_{30}$	4.55
11.20	2-Methoxy tetra hydro furane	$\text{C}_5\text{H}_{10}\text{O}_2$	0.76
12.08	1,7-Nonadiene, 4,8- dimethyl	$\text{C}_{11}\text{H}_{20}$	0.37
13.34	Naphthalene, 2-methyl-	$\text{C}_{11}\text{H}_{10}$	1.28
14.10	1,2-Diphenylcyclopropane	$\text{C}_{15}\text{H}_{14}$	2.87
14.58	Stearic acid, methyl ester	$\text{C}_{19}\text{H}_{38}\text{O}_2$	3.44
15.78	Butyrolachone	$\text{C}_4\text{H}_8\text{O}_4$	0.98
16.07	Trimethylamine	$\text{C}_3\text{H}_9\text{N}$	1.28
16.91	3-Undecene, (Z)-	$\text{C}_{11}\text{H}_{22}$	3.77
18.20	Ethisterone	$\text{C}_{21}\text{H}_{28}\text{O}_2$	3.24
19.15	1-Propene-phenyl-	$\text{C}_{10}\text{H}_{12}$	1.80
20.83	Acetonitrile, (m-phenoxyphenyl)-	$\text{C}_{14}\text{H}_{11}\text{NO}$	3.10
21.84	Carbamic acid, ethylidenebis-, diethyl ester	$\text{C}_8\text{H}_{16}\text{N}_2\text{O}$	2.74
21.99	N-(2-bromobenzoyl)-, pentyl ester	$\text{C}_{15}\text{H}_{20}\text{BrNO}_3$	0.83
23.00	Phenol, 2,4-dimethyl-	$\text{C}_8\text{H}_{10}\text{O}$	3.37
23.59	4-Undecene, (z)-	$\text{C}_{11}\text{H}_{22}$	1.25
24.73	Benzene, (1-methylethyl)-	C_9H_{12}	2.75
26.09	Cyclopentane, 1-butyl-2-propyl	$\text{C}_{12}\text{H}_{24}$	0.83
28.93	Decane, 3,6-dimethyl	$\text{C}_{12}\text{H}_{26}$	3.22
29.58	Cyclohexane, 1,3,5-trimethyl	C_9H_{18}	4.47
30.05	Tridecane	$\text{C}_{13}\text{H}_{28}$	1.68
30.61	Heneicosyl pentafluoropropionate	$\text{C}_{24}\text{H}_{43}\text{F}_5\text{O}$	5.55
32.27	1-Pentadecene	$\text{C}_{15}\text{H}_{30}$	2.87

Table 5. GC-MS study of the total pyrolysis liquid.

preheated before ignition can occur. The boiling point and melting point of the substance are found to be 488.7 °C and 42.6 °C respectively. Tetradecane is an alkane hydrocarbon. Ethisterone is a progestin that was once used to treat gynecological diseases. It is also referred to as ethinyltestosterone. It was originally marketed under the trade names Pranone and Proluton C. However, it is no longer available on the market. Stearic acid methyl ester is an esterified form of free acid that is less soluble in water but more suitable for use in the production of dietary supplements. It is a combustible substance, and based on the screening experiments, Stearic acid methyl ester is anticipated to biodegrade efficiently in aerobic waters. From the analysis of the GC–MS, it can be understood that the chemical elements identified in the liquid are combustible. The analytical findings demonstrated that the liquid oils produced by pyrolysis were very complex blends of organic substances, with a high concentration of both nitrogenated and oxygenated components. As a result, the hydrocarbon source provided by the pyrolysis products can be employed to produce high-grade liquid fuel. Following separation, the components and their derivatives found in the GC–MS study are employed as chemical feedstock for the pharmaceutical industry.

Limitation and future perspective

If waste plastics and tyre pyrolysis plants were rapidly implemented, the process would directly contribute to the reduction of greenhouse gas emissions globally to 100 million tons of CO₂-eq. Prior to the development of novel pyrolysis systems, an increased understanding of the fundamental chemistry of chemical recycling is required. From a scale-up standpoint, bridging the kinetic analysis and reactor modeling of pyrolysis technology is the most suitable way to optimally design the reactor in an industrially applicable context. Before trying to build an ideal process design for pyrolysis, it is crucial to precisely define each waste stream because the content of plastic waste differs substantially between locations. Therefore, a thorough characterization of individual feedstocks is necessary to determine the precise quantities and microstructure of each polymer species. For further study, a number of catalysts can be utilized to increase the yield and quality of liquid products. This study was conducted with the aid of fixed-bed reactors, and it can be further conducted by utilizing fluidized beds or some other reactors. It is also crucial to note that further research is still needed to analyze the potential of pyrolysis of lignocellulosic materials along with mixed plastics and waste tyres by considering social, economic and environmental conditions.

Conclusion

Nowadays, plastics are an indispensable part of everyday life and the biggest environmental pollutant. Plastic is a polymer that is difficult to break down; nonetheless, it can be broken down by thermal cracking or pyrolysis. This study examines the effect of different combinations of three different feedstocks on the amount and quality of oil output generated via individual and co-pyrolysis process. In this work, three different waste materials, such as waste furniture wood, mixed plastics and waste tyres, were utilized for individual and co-pyrolysis experiments. The study evaluated the synergistic effect on pyrolysis liquid yield during co-pyrolysis experiment. The effect of different combination of furniture wood, plastics and tyres on the products distribution during co-pyrolysis was analyzed and reported..

- The thermogravimetric analysis showed that furniture wood had a higher mass loss compared to mixed plastics and waste tyres.
- Regarding char yield, individual pyrolysis of waste tyres produced a maximum of 38.1 wt% compared to waste furniture wood and waste tyres. The yield of char was 765.9% and 39.5% higher than that of plastics and tyres.
- Co-pyrolysis of furniture wood and mixed plastics produced a higher char yield of 33.4 wt% than other combinations.
- Furniture wood wastes produced a maximum of 43.8 wt% liquid products during individual pyrolysis, which is significantly less than the output from waste tyres (47.0 wt%) and mixed plastics (70.6 wt%).
- The production of liquid yield from waste plastics is 37.9% and 33.4% higher compared to furniture wood and waste tyres.
- Through co-pyrolysis experiment, the combination of mixed plastics and waste tyres produced 7.65% more liquid than the arithmetic mean value. The positive synergistic effect recommends that the combination of mixed plastics and waste tyres can be a suitable material for higher liquid production than individual pyrolysis.
- Compared to other combinations, the yield of liquid from combining waste tyres and furniture wood was lower.
- The volatile material in the feedstock was the key factor for the positive synergistic effect to yield maximum liquid products during the pyrolysis process.
- This work fused the understanding of the effect of synergy between wood, plastics and tyres, on product yield, specifically liquid yield and liquid heating value, which favor liquid production.
- Thus, modeling the kinetics of waste furniture wood, different plastic wastes and tyre interactions during co-pyrolysis will be the primary focus of the subsequent investigation.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author and can be shared on reasonable request.

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References

- Friedlingstein, P. *et al.* Global carbon budget 2023. *Earth Syst. Sci. Data* **15**(12), 5301–5369 (2023).
- Larkin, A., Kuriakose, J., Sharmina, M. & Anderson, K. What if negative emission technologies fail at scale? Implications of the paris agreement for big emitting nations. *Clim. Policy* **18**(6), 690–714 (2018).
- Pathak, G. 'Plastic pollution' and plastics as pollution in Mumbai India. *Ethnos* **88**(1), 167–186 (2023).
- Gilbert, J. C. & Kruse, J. Playing with garbage: Exploring the nature of technology and engineering. *Sci. Scope* **46**(3), 44–50 (2023).
- Qureshi, M. S. *et al.* Pyrolysis of plastic waste: Opportunities and challenges. *J. Anal. Appl. Pyrolysis* **152**, 104804 (2020).
- Geyer, R., Jambeck, J. R. & Law, K. L. Production, use, and fate of all plastics ever made. *Sci. Adv.* **3**(7), e1700782 (2017).
- Ritchie, H., & Roser, M. (2018). Plastic pollution. Our World in Data. Retrieved from https://ourworldindata.org/plasticpollution?utm_source=newsletter.
- Kassab, A., Al Nabhani, D., Mohanty, P., Pannier, C. & Ayoub, G. Y. Advancing plastic recycling: Challenges and opportunities in the integration of 3D printing and distributed recycling for a circular economy. *Polymers* **15**(19), 3881 (2023).
- FakhrHoseini, S. M. & Dastanian, M. Predicting pyrolysis products of PE, PP, and PET using NRTL activity coefficient model. *J. Chem.* <https://doi.org/10.1155/2013/487676> (2013).
- Raguraman, D. *et al.* Performance and emission characteristics of pyrolysis oil obtained from neem de Oiled cake and waste polystyrene in a compression ignition engine. *Adv. Mater. Sci. Eng.* <https://doi.org/10.1155/2021/3728852> (2021).
- Maqsood, T., Dai, J., Zhang, Y., Guang, M. & Li, B. Pyrolysis of plastic species: A review of resources and products. *J. Anal. Appl. Pyrolysis* **159**, 105295 (2021).
- Rao, Y. K. *et al.* Investigation on forestry wood wastes: Pyrolysis and thermal characteristics of *Ficus religiosa* for energy recovery system. *Adv. Mater. Sci. Eng.* **2022**, 3314606 (2022).
- Jahirul, M. I. *et al.* Transport fuel from waste plastics pyrolysis—A review on technologies, challenges and opportunities. *Energy Convers. Manag.* **258**, 115451 (2022).
- Mohajerani, A. *et al.* Recycling waste rubber tyres in construction materials and associated environmental considerations: A review. *Resour. Conserv. Recycl.* **155**, 104679 (2020).
- Miranda, R., Yang, J., Roy, C. & Vasile, C. Vacuum pyrolysis of PVC I. Kinetic study. *Polym. Degrad. Stab.* **64**(1), 127–144 (1999).
- Liu, Y., Fu, W., Liu, T., Zhang, Y. & Li, B. Microwave pyrolysis of polyethylene terephthalate (PET) plastic bottle sheets for energy recovery. *J. Anal. Appl. Pyrolysis* **161**, 105414 (2022).
- Dhahak, A., Hild, G., Rouaud, M., Mauviel, G. & Burkle-Vitzthum, V. Slow pyrolysis of polyethylene terephthalate: Online monitoring of gas production and quantitative analysis of waxy products. *J. Anal. Appl. Pyrolysis* **142**, 104664 (2019).
- Ahmad, I. *et al.* Pyrolysis study of polypropylene and polyethylene into premium oil products. *Int. J. Green Energy* **12**(7), 663–671 (2015).
- Thomas, B. S., Gupta, R. C. & Panicker, V. J. Recycling of waste tire rubber as aggregate in concrete: Durability-related performance. *J. Clean. Prod.* **112**, 504–513 (2016).
- Chatziaras, N., Psomopoulos, C. S. & Themelis, N. J. Use of waste derived fuels in cement industry: A review. *Manag. Environ. Qual. Int. J.* **27**(2), 178–193 (2016).
- Xu, J. *et al.* High-value utilization of waste tires: A review with focus on modified carbon black from pyrolysis. *Sci. Total Environ.* **742**, 140235 (2020).
- Bockstal, L., Berchem, T., Schmetz, Q. & Richel, A. Devulcanisation and reclaiming of tires and rubber by physical and chemical processes: A review. *J. Clean. Prod.* **236**, 117574 (2019).
- Debnath, B., Chowdhury, R. & Ghosh, S. K. Sustainability of metal recovery from E-waste. *Front. Environ. Sci. Eng.* **12**(6), 1–12 (2018).
- Czajczyńska, D., Czajka, K., Krzyżyńska, R. & Jouhara, H. Waste tyre pyrolysis—Impact of the process and its products on the environment. *Therm. Sci. Eng. Prog.* **20**, 100690 (2020).
- Khudhair, M. M., Omran, R. J. & Alameer, H. A. Characterization study of liquid fuel produced from pyrolysis of waste tyres using different catalysts. In *AIP Conference Proceedings* (eds Khudhair, M. M. *et al.*) (AIP Publishing, 2020).
- Yasar, A. *et al.* Quality and environmental impacts of oil production through pyrolysis of waste tyres. *Environ. Technol. Innov.* **23**, 101565 (2021).
- Aslan, D. I., Parthasarathy, P., Goldfarb, J. L. & Ceylan, S. Pyrolysis reaction models of waste tires: Application of master-plots method for energy conversion via devolatilization. *Waste Manag.* **68**, 405–411 (2017).
- Hita, I. *et al.* Opportunities and barriers for producing high quality fuels from the pyrolysis of scrap tires. *Renew. Sustain. Energy Rev.* **56**, 745–759 (2016).
- Dhanalakshmi, C. S. *et al.* Individual and catalytic co-pyrolysis of agricultural outcomes and polymeric materials over nano-HZSM-5 Zeolite: Synergistic effects and yield analysis for heating applications. *J. Nanomater.* <https://doi.org/10.1155/2022/3743299> (2022).
- Vibhakar, C. *et al.* Production and optimization of energy rich biofuel through co-pyrolysis by utilizing mixed agricultural residues and mixed waste plastics. *Adv. Mater. Sci. Eng.* <https://doi.org/10.1155/2022/8175552> (2022).
- Kaushik, V. S., Dhanalakshmi, C. S., Madhu, P. & Tamilselvam, P. Co-pyrolysis of neem wood bark and low-density polyethylene: Influence of plastic on pyrolysis product distribution and bio-oil characterization. *Environ. Sci. Pollut. Res.* <https://doi.org/10.1007/s11356-022-21746-1> (2022).
- Martínez, J. D. *et al.* Co-pyrolysis of biomass with waste tyres: Upgrading of liquid bio-fuel. *Fuel Process. Technol.* **119**, 263–271 (2014).
- Chen, R., Lun, L., Cong, K., Li, Q. & Zhang, Y. Insights into pyrolysis and co-pyrolysis of tobacco stalk and scrap tire: Thermochemical behaviors, kinetics, and evolved gas analysis. *Energy* **183**, 25–34 (2019).
- Khan, S. R., Zeeshan, M., Khokhar, M. F., & Ahmad, I. A comprehensive study on upgradation of pyrolysis products through co-feeding of waste tire into rice straw under broad range of co-feed ratios in a bench-scale fixed bed reactor. *Biomass Convers. Biorefinery*, **13**, 4765–4765 (2023).
- Heo, H. S. *et al.* Bio-oil production from fast pyrolysis of waste furniture sawdust in a fluidized bed. *Bioresour. Technol.* **101**(1), S91–S96 (2010).
- Moreno, A. I. & Font, R. Pyrolysis of furniture wood waste: Decomposition and gases evolved. *J. Anal. Appl. Pyrolysis* **113**, 464–473 (2015).
- Sowmya Dhanalakshmi, C. & Madhu, P. Utilization possibilities of *Albizia amara* as a source of biomass energy for bio-oil in pyrolysis process. *Energy Sources A Recovery Util. Environ. Eff.* **41**(15), 1908–1919 (2019).
- Hetherington, A. C., Borrión, A. L., Griffiths, O. G. & McManus, M. C. Use of LCA as a development tool within early research: Challenges and issues across different sectors. *Int. J. Life Cycle Assess.* **19**, 130–143 (2014).
- Ahamed, A. *et al.* Environmental impact assessment of converting flexible packaging plastic waste to pyrolysis oil and multi-walled carbon nanotubes. *J. Hazard. Mater.* **390**, 121449 (2020).
- Vikram, S., Rosha, P. & Kumar, S. Recent modeling approaches to biomass pyrolysis: A review. *Energy Fuels* **35**(9), 7406–7433 (2021).
- Madhu, P., Matheswaran, M. M. & Periyannayagi, G. Optimization and characterization of bio-oil produced from cotton shell by flash pyrolysis using artificial neural network. *Energy Sources A Recovery Util. Environ. Eff.* **39**(23), 2173–2180 (2017).
- Lai, Z., Li, S., Zhang, Y., Li, Y. & Mu, J. Influence of urea formaldehyde resin on the pyrolysis of biomass components: Cellulose, hemicellulose, and lignin. *BioResources* **13**(2), 2218–2232 (2018).

43. Cai, H. *et al.* Pyrolytic kinetics, reaction mechanisms and products of waste tea via TG-FTIR and Py-GC/MS. *Energy Convers. Manag.* **184**, 436–447 (2019).
44. Lam, S. S., Liew, R. K., Lim, X. Y., Ani, F. N. & Jusoh, A. Fruit waste as feedstock for recovery by pyrolysis technique. *Int. Biodeterior. Biodegrad.* **113**, 325–333 (2016).
45. Anene, A. F., Fredriksen, S. B., Sætre, K. A. & Tokheim, L. A. Experimental study of thermal and catalytic pyrolysis of plastic waste components. *Sustainability* **10**(11), 3979 (2018).
46. Dubdub, I. & Al-Yaari, M. Thermal behavior of mixed plastics at different heating rates: I. Pyrolysis kinetics. *Polymers* **13**(19), 3413 (2021).
47. Leung, D. Y. C. & Wang, C. L. Kinetic study of scrap tyre pyrolysis and combustion. *J. Anal. Appl. Pyrolysis* **45**(2), 153–169 (1998).
48. Senneca, O., Salatino, P. & Chirone, R. A fast heating-rate thermogravimetric study of the pyrolysis of scrap tyres. *Fuel* **78**(13), 1575–1581 (1999).
49. Madhu, P., Kanagasabapathy, H. & Manickam, I. N. Flash pyrolysis of palmyra palm (*Borassus flabellifer*) using an electrically heated fluidized bed reactor. *Energy Sources A Recovery Util. Environ. Eff.* **38**(12), 1699–1705 (2016).
50. Kathir, I. *et al.* Utilization of tea industrial waste for low-grade energy recovery: optimization of liquid oil production and its characterization. *Adv. Mater. Sci. Eng.* <https://doi.org/10.1155/2022/7852046> (2022).
51. Uzun, B. B. & Kanmaz, G. Catalytic pyrolysis of waste furniture sawdust for bio-oil production. *Waste Manag. Res.* **32**(7), 646–652 (2014).
52. Madhu, P. *et al.* Production and characterization of maximum liquid oil products through individual and copyrolysis of pressed neem oil cake and waste thermocol mixture. *Adv. Polym. Technol.* **2022**, 5258130 (2022).
53. Ahmed, N., Zeeshan, M., Iqbal, N., Farooq, M. Z. & Shah, S. A. Investigation on bio-oil yield and quality with scrap tire addition in sugarcane bagasse pyrolysis. *J. Clean. Prod.* **196**, 927–934 (2018).
54. Madhu, P. *et al.* Co-pyrolysis of hardwood combined with industrial pressed oil cake and agricultural residues for enhanced bio-oil production. *J. Chem.* **2022**, 9884766 (2022).
55. Johannes, L., Tiikma, L. & Luik, H. Synergy in co-pyrolysis of oil shale and pine sawdust in autoclaves. *J. Anal. Appl. Pyrolysis* **104**, 341–352 (2013).
56. Fei, J., Zhang, J., Wang, F. & Wang, J. Synergistic effects on co-pyrolysis of lignite and high-sulfur swelling coal. *J. Anal. Appl. Pyrolysis* **95**, 61–67 (2012).
57. Zhu, X., Li, K., Zhang, L., Wu, X. & Zhu, X. Synergistic effects on thermochemical behaviors of co-pyrolysis between bio-oil distillation residue and bituminous coal. *Energy Convers. Manag.* **151**, 209–215 (2017).
58. Demirbas, A. Effects of moisture and hydrogen content on the heating value of fuels. *Energy Sources A Recovery Util. Environ. Eff.* **29**(7), 649–655 (2007).
59. Islam, M. N., Joardder, M. U. H., Hoque, S. N. & Uddin, M. S. A comparative study on pyrolysis for liquid oil from different biomass solid wastes. *Proced. Eng.* **56**, 643–649 (2013).
60. Naima, K. & Liazi, A. Waste oils as alternative fuel for diesel engine: A review. *J. Pet. Technol. Alternative Fuels* **4**(3), 30–43 (2013).
61. Mia, M., Islam, A., Rubel, R. I. & Islam, M. R. Fractional distillation & characterization of tire derived pyrolysis oil. *Int. J. Eng. Technol. IJET* **3**(1), 1–10 (2017).
62. Madhu, P., Neethi, M. I. & Kanagasabapathy, H. Parametric analysis of cotton shell and palmyra palm fruit bunch for bio oil in fixed bed pyrolysis system. *Int. J. Appl. Environ. Sci.* **9**(5), 2427–2436 (2014).
63. Suntivarakorn, R., Treedet, W., Singbua, P. & Teeramaetawat, N. Fast pyrolysis from Napier grass for pyrolysis oil production by using circulating Fluidized Bed Reactor: Improvement of pyrolysis system and production cost. *Energy Rep.* **4**, 565–575 (2018).
64. Kumar, P. M., Uvaraja, V. C. & Madhu, P. Effect of Al₂O₃/PSZ and Al₂O₃/YSZ ceramic coating in CI engine fueled with ternary blends of castor seed oil and jatropa oil biodiesel dosed with diesel. *J. Ceram. Process. Res.* **23**(5), 647–655 (2022).
65. Yan, G., Jing, X., Wen, H. & Xiang, S. Thermal cracking of virgin and waste plastics of PP and LDPE in a semibatch reactor under atmospheric pressure. *Energy Fuels* **29**(4), 2289–2298 (2015).
66. Adrados, A. *et al.* Pyrolysis of plastic packaging waste: A comparison of plastic residuals from material recovery facilities with simulated plastic waste. *Waste Manag.* **32**(5), 826–832 (2012).
67. Siddiqui, M. N. & Redhwi, H. H. Pyrolysis of mixed plastics for the recovery of useful products. *Fuel Process. Technol.* **90**(4), 545–552 (2009).
68. Singh, R. K., Ruj, B., Sadhukhan, A. K. & Gupta, P. Impact of fast and slow pyrolysis on the degradation of mixed plastic waste: Product yield analysis and their characterization. *J. Energy Inst.* **92**(6), 1647–1657 (2019).
69. Zhao, B., Zhao, Y., Wu, M., Li, X. & Li, B. Ab initio studies on the vibrational spectra and conformational isomerism of 2, 4-dimethyl-1, 3-pentadiene. *Spectrochim. Acta A Mol. Biomol. Spectrosc.* **56**(4), 671–679 (2000).

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Additional information

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