



Production and characterization of bio-oil from camelthorn plant using slow pyrolysis

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Abstract

In this study, slow pyrolysis of the camelthorn plant process was conducted to produce bio-oil, biochar, and gas. The pyrolysis process was conducted between 400 and 550 °C under pressure 10 bar using a fixed bed reactor. The pyrolysis products were bio-oil, biogas, and biochar. These products were characterized using Fourier-transform infrared (FT-IR) model, gas analyzer, chromatographic analysis using GC–MS, and thermogravimetric analysis (TGA). The GC–MS results demonstrated composition of bio-oil, detecting several organic substances including levoglucosan, furan, acetic acid, phenol, and long-chain hydrocarbon. To further understand the chemical composition of bio-oil, FT-IR spectroscopy was conducted to determine functional groups. The thermal behavior and degradation of the camelthorn sample were studied using TGA which provided thermal stability and prospective applications. Gas composition was measured using a gas analyzer. These analytical methods' results offer insight on the camelthorn plant's potential as a sustainable bio-oil and biochar sources, and these findings contribute to the advancement of biomass conversion expertise and provide vital insights for sustainable energy production.

Keywords Biomass · Bio-oil · Renewable source · Slow pyrolysis

Introduction

The recent rapid increase in consumption of energy, along with the ongoing depletion of fossil fuel supply, has triggered a global search for renewable energy sources. Biomass is a viable choice due to its sustainability and environmental friendliness [1]. Renewable energy sources are varied and diverse, encompassing wind energy, solar energy, and biomass. These sources offer sustainable alternatives to fossil fuels, contributing to environmental preservation and energy security [2]. Biomass has been identified as a potentially renewable source of energy capable of producing a wide range of chemicals and materials [3]. The benefits of biomass over traditional fossil fuels include low sulfur and nitrogen contents and zero net CO₂ emissions to the atmosphere. Biomass has been identified as a potentially renewable source of energy capable of producing a wide range of chemicals and materials. Renewable energy, including biomass, can be harnessed for various applications such as water desalination using membrane distillation. This demonstrates the versatility and sustainability of renewable energy sources in addressing diverse global challenges [4]. Forest residues, energy crops, organic wastes, agricultural residues, and other materials are examples of biomass resources.

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Agricultural waste, a widely available biomass, is produced worldwide on a yearly basis and is severely underutilized [5]. Agricultural biomass residues are rich in energy and are made of cellulose, hemicellulose, and lignin. Agricultural biomass waste holds significant potential as a renewable energy source, consisting of cellulose, hemicellulose, and lignin. Bioenergy derived from both conventional and innovative techniques applied to biomass is promising for heating, transportation, and electricity, while also ensuring environmental sustainability. Bioenergy currently provides approximately 24×10^{18} J of energy, making it the largest renewable energy source, accounting for 10% of the world's total energy consumption. By 2050, bioenergy is expected to play a crucial role in achieving a carbon net-zero economy, with a potential supply increase to 313×10^{18} J, or 37% of global energy demand [6]. Biomass can be converted into high-value fuels and chemicals using thermochemical and biochemical conversion technologies. This includes a variety of renewable resources such as crop residues, wood and forestry residues, municipal solid waste, spent coffee grounds, and other agricultural waste, which can be utilized for producing biofuels and hydrogen. Pyrolysis offers a sustainable method for converting agricultural waste into valuable products. Optimizing pyrolysis processes, scaling up operations, and reducing costs are crucial for enhancing biofuel productivity and economic viability.

Extensive research on biomass characterization has shown that pyrolysis is an efficient method for converting heavy metal-contaminated biomass into valuable products. This process not only enhances the sustainability of phytoremediation practices but also generates valuable by-products.

Camelthorn plant is one of the agricultural biomasses that could be utilized to make liquid, solid, and gas biofuels. The scientific term for camelthorn is *Alhagi maurorum*, and it is a member of the pea family. This aggressive, deep-rooted plant may rapidly take over both distributed and unattended regions, outcompeting native species, diminishing plant diversity and wildlife habitat, and establishing massive monocultures. It possesses spines that can injure humans, dogs, and cattle and are sharp enough to puncture tires as shown in Fig. 1. It has the ability to penetrate concrete and pavement. It is a perennial desert plant that was brought to the USA from Western Asia and the Mediterranean. The earliest infestations were discovered in California, and they have since spread to many other western states. Camelthorn is a noxious weed in a number of states, including Arizona. A noxious weed is one that is not native to the ecosystem and is invasive [7–10].

Thermochemical techniques such as combustion, torrefaction, hydrothermal liquefaction, pyrolysis, and gasification are used for biomass conversion as shown in Fig. 2.

By optimizing the process conditions, thermochemical conversion aims to remove undesired by-products [14].



Fig. 1 Camelthorn plant

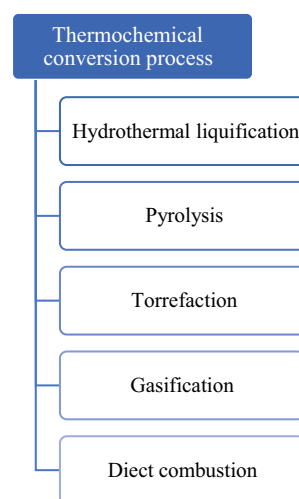


Fig. 2 Thermochemical conversion process

Pyrolysis is an effective process used to transform raw biomass into biofuel at temperatures between 400 and 600 °C [15]. Recently, the pyrolysis process of biomass has been utilized to produce bio-based chemicals and biofuels. Bio-char, biofuel, and gaseous products can be obtained from biomass pyrolysis in the absence of oxygen [16]. These three products are considered sources of energy for several applications due to their eco-friendly nature and low costs [17]. Bio-oil, a liquid with a dark brown color, consists of acids, alcohols, esters, ketones, phenols, aldehydes, and oligomers [18]. However, bio-oil has drawbacks, such as high water and ash content, corrosiveness, and high viscosity [19]. The low fuel quality of bio-oil is a significant obstacle impeding its commercialization [20]. Most early studies as well as current work focus on improving the quality of bio-oil. It was reported that the quality of bio-oil was enhanced using rice husk pyrolysis [21]. The enhanced oil's density decreased from 1.24 to 0.95 g cm⁻³, and its heating value increased from 16.0 to 27.2 MJ kg⁻¹. However, the oil's pH decreased from 4.4 to 2.3 after the refinement process [22].

There are two kinds of gaseous biofuels: syngas and biohydrogen. The primary solid product is biochar, which is produced from biomass thermal degradation, typically within the temperature range of 350–700 °C. Biochar can be used for various applications such as fertilizer, catalyst for chemical processes, adsorbent in wastewater treatment, energy storage, and supercapacitors [23, 24].

Pyrolysis is classified into 3 categories: fast pyrolysis, slow pyrolysis, and flash pyrolysis. Table 1 illustrates the parameters that affect pyrolysis process in terms of slow, fast, and flash pyrolysis. Palm kernel cake achieved a 63% bio-oil yield via fast pyrolysis in a fluidized bed reactor at 401 °C [25] and an impressive 73.74% yield using flash pyrolysis in an entrained-flow reactor (EFR) at 600 °C [26]. Rapeseed straw, processed through fast pyrolysis in a fluidized bed reactor at 450 °C, resulted in a 41.39% bio-oil yield [27]. Sugarcane bagasse yielded 50.89% and 26.11% bio-oil via fast and slow pyrolysis, respectively, using a batch pyrolysis reactor at 455 °C [28]. Corn cob fast pyrolysis in a microwave-assisted reactor yielded 42.1% bio-oil [29]. Additionally, sawdust processed through an unspecified pyrolysis method yielded 40.2% bio-oil [29]. Bio-oil yields from various biomass sources using different pyrolysis techniques and reactors are listed in Table 1. Rice straw subjected to slow pyrolysis in a laboratory-scale packed bed reactor produced a bio-oil yield of 30–40% at temperatures between 300 and 700 °C [30], while another pyrolysis method yielded 15.3% at 400–500 °C [29].

Each one of these parameters produced bio-oil, biochar, and biogas with different yields. Temperature in slow pyrolysis varies from 450 to 550 °C which, so it produces low quality of bio-oil and produces high amount and quality of biochar, so it produces biochar as a primary product, along with gas and small amount of bio-oil. Fast pyrolysis produces the highest quality and amount of bio-oil due to its high temperature, high heating rate, and low residence time. An increase in temperature increases the oil yield and lowers the char yield. The temperature should

be moderate, not very high and not low, because if it is very high it will produce a high amount of oil but of a low quality. These three classifications are often used in the context of biomass pyrolysis. Each type of pyrolysis has its own advantages and disadvantages depending on the type of material being processed and the desired products [31]. Currently, flash and fast pyrolysis techniques are under development and moving toward commercialization. These methods are designed to meet specific requirements, such as a high heating rate and the efficient separation of solid, liquid, and gas products. Fixed bed pyrolysis of biomass is commonly employed in research settings [32]. Fixed bed reactor or packed bed pyrolysis is a process used to convert organic materials, such as biomass into liquid, gas, and solid products through thermal decomposition in the absence of oxygen. The process was conducted in fixed bed reactor vessel. The dried camelthorn agricultural waste was fed into the top of the reactor, where it was heated in the presence of the hotbed material. As the material decomposed, it released volatile gases, including hydrogen, methane, and other hydrocarbons, as well as liquid products, commonly known as pyrolysis oil or bio-oil, and solid residue, commonly known as char. Up to our knowledge, no one has worked on the pyrolysis of camelthorn agricultural waste.

Materials and methods

In this research, an analysis of camelthorn plant pyrolysis at three different temperatures 400 °C, 500 °C, and 550 °C was conducted. The composition of camelthorn includes crude protein, crude fiber, neutral detergent fiber (NDF). It comprises hemicellulose, cellulose, and lignin—lignin as a component of NDF, and ash, as listed in Table 2. The mineral composition is presented in Table 3 [11–13].

Table 1 Production of bio-oil using different pyrolysis techniques and biomass sources

Source of biomass	Type of pyrolysis	Type of reactor	Yield of bio-oil/mass%	Temperature/°C	References
Palm kernel cake	Fast	Fluidized bed reactor	63	401	[25]
Palm kernel cake	Flash pyrolysis	Entrained-flow reactor (EFR)	73.74	600	[26]
Rapeseed straw	Fast pyrolysis	Fluidized bed reactor	41.39	450	[27]
sugarcane bagasse	Batch pyrolysis reactor	Fast pyrolysis	50.89	455	[28]
sugarcane bagasse	Batch pyrolysis reactor	Slow Pyrolysis	26.11	455	
Corn Cob	Fast Pyrolysis	Microwave-assisted reactor	42.1	400–500	[29]
Saw dust			40.2		
Rice straw			15.3		
Rice straw	Slow pyrolysis	A laboratory-scale packed bed reactor	30–40	300–700	[30]

Table 2 Main analysis of camelthorn plant

Main analysis	Average (% DM)
Crude protein	8.5
Crude fiber	31.8
Neutral detergent fiber (NDF)	49.7
Lignin	5.9
Ash	6

Table 3 Minerals found in camelthorn plant

Minerals	Average/g Kg ⁻¹ DM
Calcium	6.6
Phosphorus	1.3
Potassium	0.3
Sodium	0.1
Magnesium	1.2
Manganese	8
Zinc	18
Copper	4
Iron	167

Material preparations

The feedstock utilized in this research (camelthorn) can be categorized as agricultural waste. The plants were collected in June from Port Said, Egypt, located at a latitude of 31.16° North and a longitude of 32.18° East. The camelthorn plant is toxic due to the presence of alkaloids and other compounds that can be harmful to animals and humans if ingested. Accordingly, it is preferable to convert it into a useful product, such as bio-oil, rather than leaving it in its natural state. This conversion process not only mitigates the plant's harmful effects but also generates a valuable resource. The initial step after collecting the plant involved cutting it into smaller pieces, with an average particle size of 5 cm. (1) Smaller particles have a greater surface area relative to their volume, which increases the efficiency of chemical and biological processes that break down the plant material. This makes it easier to convert the plant into bio-oil. (2) Consistent and smaller particle sizes ensure a more uniform feedstock for the conversion process, leading to higher quality and more predictable bio-oil output. In the second step, the biomass was dried at 70 °C for 24 h to reduce its water content. The presence of water in the biomass can lead to increased moisture in the resulting bio-oil. High moisture content in bio-oil lowers its energy density and heating value, making it less efficient as a fuel. Therefore, reducing the water content in the biomass prior to pyrolysis is crucial for improving the quality and efficiency

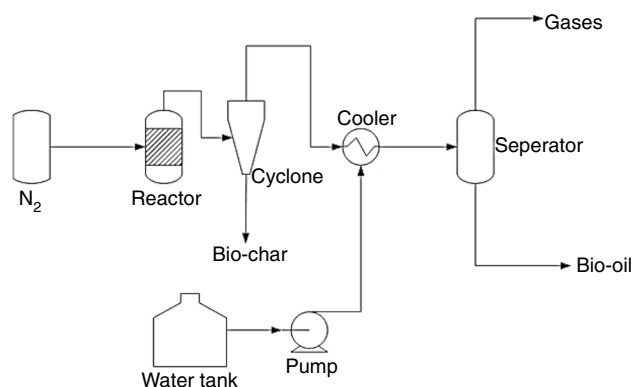
of the produced bio-oil. Then, the biomass was fed into a pyrolysis reactor. This uniformity helps in achieving better control over the conversion parameters and the properties of the final product. By following this method, the toxic camelthorn plant can be effectively transformed into a beneficial product, thereby addressing both environmental and economic concerns.

Pyrolysis process

As illustrated in Fig. 3, the reactor was internally cleaned to remove any contaminants or leftover residue. Then, with the aid of a gas tube, nitrogen was compressed into the reactor to inhibit the presence of oxygen since the pyrolysis process thrives in the absence of oxygen, as well as neglecting the probability of the occurrence of a combustion reaction. Feedstock was fed in the form of three batches at three temperatures: 400 °C, 500 °C, 550 °C at a uniform pressure of 10 bar. The temperature was measured and maintained using Midi Logger GI220. Precisely, the temperature was increased by feeding the reactor from the gas tube and measured continuously. The pyrolysis process should result in the formation of biochar, bio-oil, and gas. Firstly, the biochar was collected from the bottom of the cyclone, the rest of the stream went into the cooler, then in a separator to separate the bio-oil in the downstream and the biogas in the upstream. The cooling process was maintained using water as a cooling utility stream to initiate heat transfer and cool down the injected gas. The water, with the help of a centrifugal pump, was pumped into the heat exchanger. The gas was collected in the gas cylinder as shown in Fig. 3. It was analyzed to determine its composition using the IMR gas analyzer.

Functional groups of pyrolysis bio-oils

Fourier-transform infrared spectroscopy (FT-IR) analysis is a valuable approach for determining the chemical composition of bio-oil produced from the camelthorn plant by

**Fig. 3** Pyrolysis process using camelthorn plant

pyrolysis. To determine the functional groups, the bio-oil samples were studied using VERTEX 80v vacuum FT-IR spectrometer. The absorption of infrared radiation at different wavelengths was measured. The resulting spectrum has peaks at various wavelengths that correlate with various functional groups in the sample. The wavelength range employed for FT-IR analysis of bio-oil was $4000\text{--}450\text{ cm}^{-1}$. In FT-IR, the absorbance unit is commonly measured in terms of absorbance (A) or transmittance ($\%T$). Absorbance is a proportional indicator of how much radiation a sample absorbs and is proportional to the concentration of the absorbing species [32, 33].

Chromatographic analysis using chromatography-mass spectrometry

Chromatographic analysis utilizing GC–MS was carried out using Agilent Technologies 7890B GC Systems in conjunction with a 5977A Mass Selective Detector. The analysis employed a capillary column (HP-5MS Capillary; dimensions: $30.0\text{ m} \times 0.25\text{ mm ID} \times 0.25\text{ }\mu\text{m film}$), and helium was used as the carrier gas at a pressure of 7.6 psi, with an injection volume of $1\text{ }\mu\text{L}$. Upon injection, the sample was subjected to analysis with an initial column temperature of $60\text{ }^{\circ}\text{C}$ for a duration of 3 min. Subsequently, the temperature was raised to $300\text{ }^{\circ}\text{C}$ at a heating rate of $20\text{ }^{\circ}\text{C min}^{-1}$, and this temperature was maintained for 5.0 min. The injection was conducted in split-less mode at $300\text{ }^{\circ}\text{C}$. The mass spectrometry (MS) scan was conducted in the range of m/z 50–550 atomic mass units (AMU) using electron impact (EI) ionization at 70 eV, with a solvent delay of 4.0 min.

The constituents were identified through mass fragmentation patterns using The NIST mass spectral search program, referencing the NIST/EPA/NIH mass spectral library Version 2.2 (June 2014).

Fourier-transform infrared spectroscopy (FT-IR)

Fourier-transform infrared spectroscopy (FT-IR) analysis is a valuable approach for determining the chemical composition of bio-oil produced from the camelthorn plant by pyrolysis. To determine the functional groups present samples collected at $400\text{ }^{\circ}\text{C}$, $500\text{ }^{\circ}\text{C}$, and $550\text{ }^{\circ}\text{C}$. The absorption of infrared radiation at different wavelengths was measured. The resulting spectrum has peaks at various wavelengths that correlate with various functional groups in the sample. Fourier-transform infrared spectroscopy (FT-IR) measurements were carried out using a BRUKER ALPHA II spectrometer equipped with an attenuated total reflection (ATR) platinum crystal. For each sample, 24 high-resolution scans were taken with a resolution of 4 cm^{-1} to ensure detailed and accurate spectral analysis. Absorbance is a proportional indicator of how much radiation a sample absorbs and is

proportional to the concentration of the absorbing species. In the case of pyrolysis-extracted bio-oil, the FT-IR spectrum showed the functional groups existing in the sample, including hydroxyl groups ($-\text{OH}$), carbonyl groups ($-\text{C}=\text{O}$), and aromatic compounds, which can aid in optimizing the pyrolysis process for highest yield and quality.

Thermal stability

The thermal stability of camelthorn agricultural waste was investigated using a thermogravimetric analyzer (LABSYS evo—Setaram). Throughout the thermogravimetric analysis (TGA) procedure, nitrogen gas was utilized as the inert atmosphere to prevent oxidation. The sample was subjected to a controlled heating rate of $10\text{ }^{\circ}\text{C min}^{-1}$, starting from room temperature ($25\text{ }^{\circ}\text{C}$) and increasing up to $970\text{ }^{\circ}\text{C}$. Once the temperature reached $970\text{ }^{\circ}\text{C}$, it was maintained until a stable state was achieved. The heating process was designed to observe the thermal degradation behavior of the camelthorn plant's primary components: hemicellulose, cellulose, and lignin. Monitoring the breakdown of these constituents provided valuable insights into the thermal stability and composition of the biomass, which was crucial for understanding its suitability for various applications such as biofuel production [34, 35].

Scanning electron microscopy analysis and energy-dispersive X-ray

Surface morphology and elemental analysis of biochar samples were conducted using a MIRA-TESCAN SEM (manufactured by Tescan Essence company, Brno), in conjunction with an energy-dispersive X-ray (EDX) analyzer from Oxford Instruments Nano Analysis (UK) to perform elemental analysis. Prior to imaging, the samples were dried and coated with a 10 nm layer of gold/palladium alloy using a Quorum mini sputter coater (SC7620). Energy-dispersive X-ray (EDX) measurements were conducted at an energy of 5 keV. Measurements were recorded at three different locations on each sample and averaged to ensure accuracy.

Results and discussions

Results of this process were discussed for 2100 g of camelthorn plant biomass, 700 g for each sample. Three batches of raw material were fed to pyrolysis reactor at temperatures at $400\text{ }^{\circ}\text{C}$, $500\text{ }^{\circ}\text{C}$, and $550\text{ }^{\circ}\text{C}$.

Physical properties of oil

Bio-oil is a multifaceted compound, characterized by a variety of properties that collectively define its composition and

Table 4 Physical properties of bio-oil

	Collected at 400 °C	Collected at 500 °C	Collected at 550 °C
pH	4.2	4.08	3.92
Density/g cm ⁻³	0.91	0.95	0.97
Viscosity	1.5	1.6	1.8

behavior. These properties were systematically investigated, and their outcomes are outlined in Table 4.

One of the notable properties studied was the pH of the bio-oil. To measure the pH, the analysis was conducted at a specific temperature of 30 °C. Interestingly, a distinct trend emerged from the observations. It became evident that the pH of the bio-oil exhibited a direct correlation with temperature variations. As the temperature of pyrolysis increases, the pH of the resulting bio-oil tends to decrease. This trend is visually illustrated in the listed results, where it was clearly demonstrated that at a temperature of 550 °C, the pH value was 3.92. This phenomenon can be explained by the fact that pyrolysis involves the thermal decomposition of organic materials, such as biomass, into smaller molecules like bio-oil [36]. During this process, various acidic and basic compounds were formed as a result of the breakdown of organic components. At higher temperatures, there is a greater likelihood of certain acidic compounds being generated, leading to a decrease in pH. The concentration of these acidic components increases as the temperature rises, which consequently lowers the pH value of the bio-oil.

Additionally, the density of bio-oil was measured. The comparison indicated that bio-oil boasts a higher density compared to the density of traditional fossil fuels. The density of bio-oil was reported around 0.95 g cm⁻³, while that of conventional fossil fuels stood at 0.8 g cm⁻³. This discrepancy in density is noteworthy as it can have implications for various applications and processes involving these substances. The higher density of bio-oil could influence its combustion characteristics, energy content, and transport considerations.

The density was measured by the following equation:

$$\rho = \frac{\Delta \text{mass}}{\text{volume}}$$

Δwhere mass = mass of the empty bottle-mass of oil inside of the bottle. The relationship between density and temperature can be understood through changes in the composition of the bio-oil during pyrolysis. As the temperature increased, more volatile and lighter components tended to evaporate or decompose as listed in Table 4. This results in a bio-oil composition that was relatively enriched in heavier, less volatile compounds. These heavier compounds are likely to have higher molecular weights and therefore contribute to

an overall higher density of the bio-oil at elevated pyrolysis temperatures [37].

Biofuel composition

A comprehensive analysis of the GC–MS outcomes, as listed in Tables 5–7, indicates the chemical constituents present in bio-oil derived from camelthorn plant pyrolyzed at 400 °C, 500 °C, and 550 °C. Specifically, notable percentages were found in the CHCl₃, C₇H₁₂O, C₇H₈O₂, and C₇H₈O. The major components of bio-oil derived from the camelthorn plant at 400 °C include phenol (18.14%), m-guaiacol (25.16%), phenol 3-methyl (14.43%), 2,4-dimethylfuran (9.06%), and oleic acid (0.28%). Phenol is a crucial compound due to its anti-septic properties. It is used as a precursor in the production

Table 5 GC–MS analysis of biofuels production from camelthorn plant at temperature 400 °C

Component	mass%
2-Methyl-2-vinylloxirane	0.9537
2,4-Dimethylfuran	5.3971
Trichloromethane	0.1707
2,4-Dimethylfuran	3.6604
Phenol	18.1424
m-Guaiacol	25.1642
Phenol, 3-methyl-	14.4321
O-Methoxy-.alpha.-methylbenzyl alcohol	3.8599
Phenol, 4-ethyl-	0.985
3-Methylpenta-1,3-diene-5-ol, (E)-	1.3654
Ethanone, 1-(4-methyl-1H-imidazol-2-yl)-	1.7771
5H-Cyclohepta-1,4-dioxin, 2,3,4a,6,7,9a-hexahydro-, cis-[1,2,3,4]Tetrazolo[1,5-a]pyridine-6-carboxylic acid	0.7699
2-Hexen-4-yn-1-ol, (E)-	0.12
2-Propanone, 1-(4-hydroxy-3-methoxyphenyl)-	1.7625
Ethanone, 1-(2,5-dihydroxyphenyl)-	0.1563
2-Butyenedioic acid, di-2-propenyl ester	0.6942
n-Hexadecanoic acid	0.427
2(1H)-Benzocyclooctenone, decahydro-4a-methyl-, trans-(-)-	0.4405
Oleic Acid	0.2751
n-Propyl 11-octadecenoate	4.136
trans-13-Octadecenoic acid	5.5819
Ethyl 5-(furan-2-yl)-1,2-oxazole-3-carboxylate	2.3286
n-Propyl 11-octadecenoate	2.814
MDMA methylene homolog	2.4109
n-Propyl 11-octadecenoate	1.0571
n-Propyl 11-octadecenoate	0.3058
E-2-Methyl-3-tetradecen-1-ol acetate	0.0831
9-Octadecenoic acid (Z)-, 2,3-dihydroxypropyl ester	0.2535
Propylene glycol monooleate	0.0281
trans-13-Octadecenoic acid	0.0379

Table 6 GC–MS analysis of biofuels production from camelthorn plant at temperature 500 °C

Component	mass%
Furan, 3-methyl-	0.5942
2,4-Dimethylfuran	4.9329
2-Cyclopenten-1-one, 3-methyl-	7.1986
Phenol	21.0187
m-Guaiacol	12.5462
Mequinol	15.4849
1-Hexen-3-yne, 2-methyl-	15.416
Ethanone, 1-(2,5-dihydroxyphenyl)-	6.0706
(E)-pent-2-en-3-yl acetate	1.7465
7-Methoxy-6-nitro-2H-1,3-benzodioxole-5-carboxylic acid	3.4387
Phenol, 4-methoxy-3-(methoxymethyl)-	1.7346
Benzaldehyde,-2-ethoxy-5-methoxy	1.7679
2,5-Cyclohexadiene-1,4-dione, 3-hydroxy-2-methyl-5-(1-methylethyl)-	0.4915
n-Hexadecanoic acid	0.3918
8-Hexadecenal, 14-methyl-, (Z)-	0.3794
Caparratriene	0.212
9-Octadecenoic acid, (E)-	2.7388
MDMA methylene homolog	3.7419
Oleic Acid	0.0948

Table 7 GC–MS analysis of biofuels production from camelthorn plant at temperature 550 °C

Component	mass%
Trichloromethane	20.43
cis-2-Ethyl-2-hexen-1-ol	0.5296
Furan, tetrahydro-3-methyl-4-methylene-	0.2897
1,3-Butadiene-1-carboxylic acid	0.2331
2-Pentenal, 2-ethyl-	10.5328
2-Pentyn-1-ol	5.2446
Phenol	2.2559
Phenol	2.9061
m-Guaiacol	11.8232
m-Guaiacol	1.5945
Mequinol	5.2021
m-Guaiacol	7.819
<i>p</i> -Cresol	8.9842
Phenol, 3-methoxy-2-methyl-	1.7709
5-Isopropyl-2H-pyrazole-3-carbaldehyde	2.0176
9-Octadecenoic acid (Z)-, 2,3-dihydroxypropyl ester	3.4826
Ethyl 5-(furan-2-yl)-1,2-oxazole-3-carboxylate	3.3666
Propanamide, N-(3-methoxyphenyl)-2,2-dimethyl-	1.8496
MDMA methylene homolog	1.2098
5-Octen-2-one, 6-methyl-8-(2,6,6-trimethyl-1-cyclohexen-1-yl)-	4.7346
9-Octadecenoic acid, (E)-	0.952
Ethyl 5-(furan-2-yl)-1,2-oxazole-3-carboxylate	2.7713

of plastics and pharmaceuticals. The high concentration of m-guaiacol makes this bio-oil valuable for flavoring and fragrances as well as an intermediate in the synthesis of other chemicals. Phenol 3-methyl is used in the manufacturing of resins and as a chemical intermediate, while 2,4-dimethylfuran is notable as a potential biofuel additive because of its high energy content. Although oleic acid is found in smaller quantities, it is utilized in the production of soaps and as an emulsifying agent. The bio-oil produced at 400 °C is rich in phenolic compounds which are valuable for industrial applications. The presence of furan derivatives further enhanced its potential as a biofuel additive. When the pyrolysis temperature was increased to 500 °C, the composition of bio-oil showed significant changes. Phenol concentration increased to 21.02% which enhanced its industrial value. M-guaiacol decreased slightly to 12.55% but remains significant for its applications in the flavor and fragrance industries. The emergence of mequinol at 15.48% added value as it is used as a topical antiseptic and in chemical synthesis. The presence of 1-hexen-3-yne, 2-methyl (15.42%) introduced a chemical intermediate with various industrial applications. Additionally, 2-cyclopenten-1-one, 3-methyl (7.20%) became important for organic synthesis and as a flavoring agent. Ethanone, 1-(2,5-dihydroxyphenyl)- (6.07%) offers potential pharmaceutical applications. The higher temperature resulted in a more diverse array of compounds. Increasing the concentrations of phenolic and aromatic compounds made the bio-oil more suitable for industrial chemical applications. At 550 °C, the bio-oil composition shifted again with trichloromethane becoming a major component at 20.43%. This compound indicated potential for use as a solvent. The presence of 2-pentenal, 2-ethyl (10.53%) is useful in the flavor and fragrance industries, while m-guaiacol remained significant at 11.82%. The appearance of *p*-cresol at 8.98% added value for its use in disinfectants and as a chemical intermediate. Additionally, the compound 5-octen-2-one, 6-methyl-8-(2,6,6-trimethyl-1-cyclohexen-1-yl)- (4.73%) is used in perfumes and flavorings. At 550 °C, the prominence of trichloromethane was notable suggesting potential industrial applications. However, it also necessitates careful handling due to its hazardous nature. The diversity of compounds at 550 °C suggested more complex reactions were occurring producing valuable intermediates for various chemical industries.

Each pyrolysis temperature produces a unique profile of bio-oil, with specific components targeted for different industrial applications as shown in Figs. 4–6. At 400 °C, the bio-oil is rich in phenols and furans, making it suitable for industrial chemicals and potential biofuel additives. At 500 °C, the bio-oil became richer in diverse phenolic and aromatic compounds enhancing its suitability for industrial chemical applications. At 550 °C, the bio-oil contained significant amounts of trichloromethane and other

Fig. 4 GC–MS spectra of pyrolysis oil at 400 °C

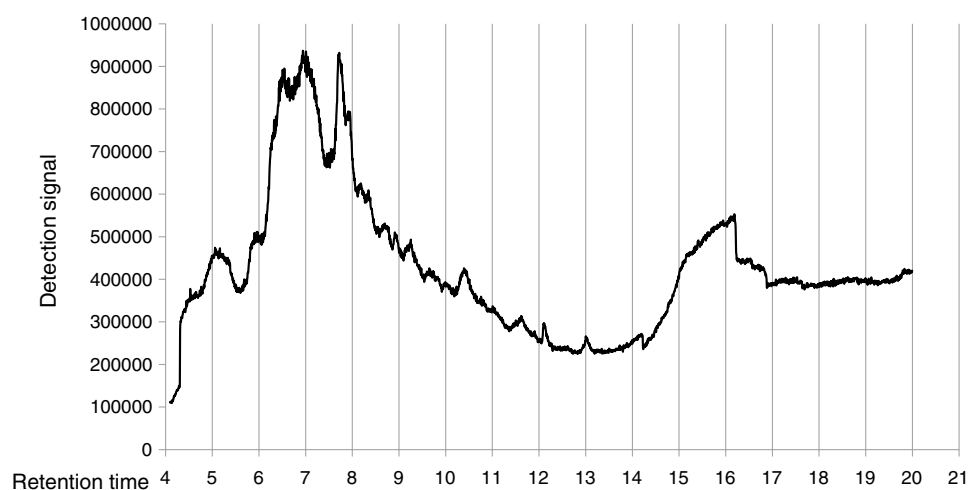


Fig. 5 GC–MS spectra of pyrolysis oil at 500 °C

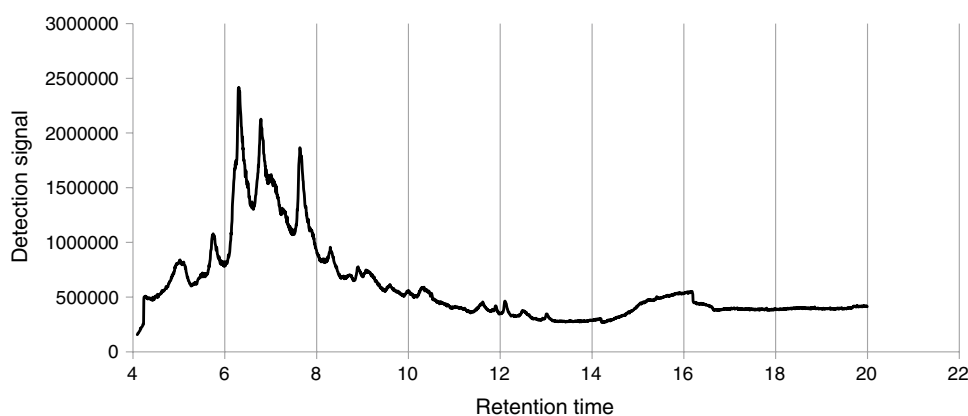
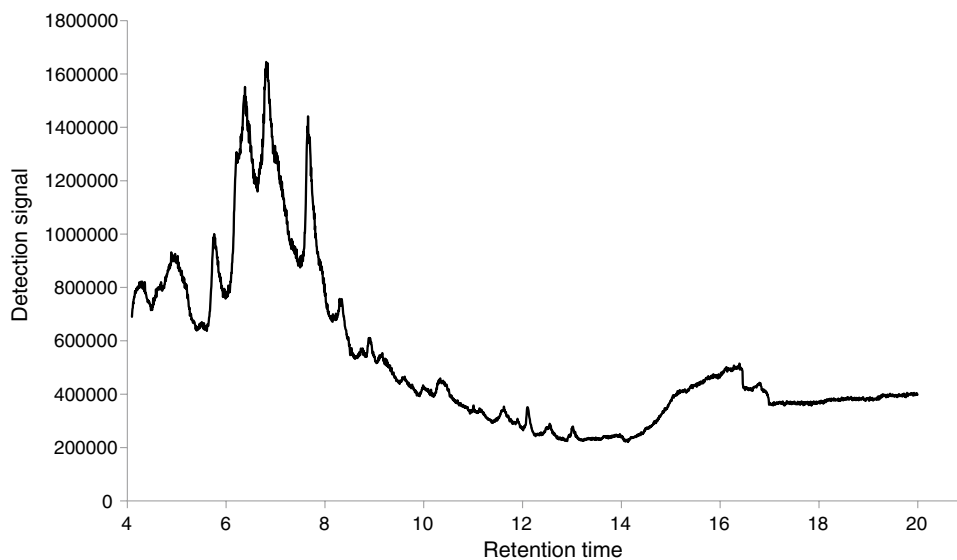


Fig. 6 GC–MS spectra of pyrolysis oil at 550 °C



complex compounds which have various industrial applications. The variations in bio-oil composition at different temperatures enhanced the overall value and utility of the pyrolysis process and offered versatile materials for a wide range of applications.

Fourier-transform infrared spectroscopy (FT-IR) results

Fourier-transform infrared spectroscopy (FT-IR) results are shown in Fig. 7. Function groups are listed in Table 8. Figure 7 illustrates the wavenumber and absorbance units of three different samples of bio-oil extracted from camelthorn plant at three different temperatures, sample (1): 400 °C, sample (2): 500 °C, and sample (3): 550 °C. Table 8 shows the functional groups that may be recognized. It is not unexpected that all samples exhibited similar spectra and shared several functional groups. The diagram can be, mainly, split into 3 peaks. The first peak occurred between 400 and 3000 cm^{-1} wavenumber with the green curve showing the highest absorbance (between 0.31 and 0.35), and Table 8 indicates the presence of alcohol, and phenols, followed by blue and purple curves with absorbance around 0.18.

The last highest peak curve between 700 and 450 cm^{-1} wavelength shows the green curve exhibiting the highest absorbance and presence of aromatic rings. Fourier-transform infrared spectroscopy (FT-IR) analysis serves as an invaluable technique for unraveling the chemical composition of bio-oil, a product derived from camelthorn plant pyrolysis. This method offered crucial insights into the bio-oil's functional groups through the measurement of infrared radiation absorption at various wavelengths. The resulting FT-IR spectrum showcases distinctive peaks at different wavelengths, each corresponding to specific functional groups present within the sample. The analysis of bio-oil typically spans a wavelength range of 4000–450 cm^{-1} . In this analysis, the unit of absorbance is often expressed as either absorbance (A) or transmittance ($\%T$). In the context of bio-oil extracted through pyrolysis, the FT-IR spectrum offers valuable insights into the types of functional groups existing within the sample. These may encompass hydroxyl groups ($-\text{OH}$), carbonyl groups ($-\text{C}=\text{O}$), and aromatic compounds. The FT-IR spectra listed in Table 8 provided a visual representation of the wavenumber and absorbance units for three distinct bio-oil samples from the camelthorn plant, each produced at varying temperatures: sample (1) at 400 °C, sample

Fig. 7 FT-IR spectra

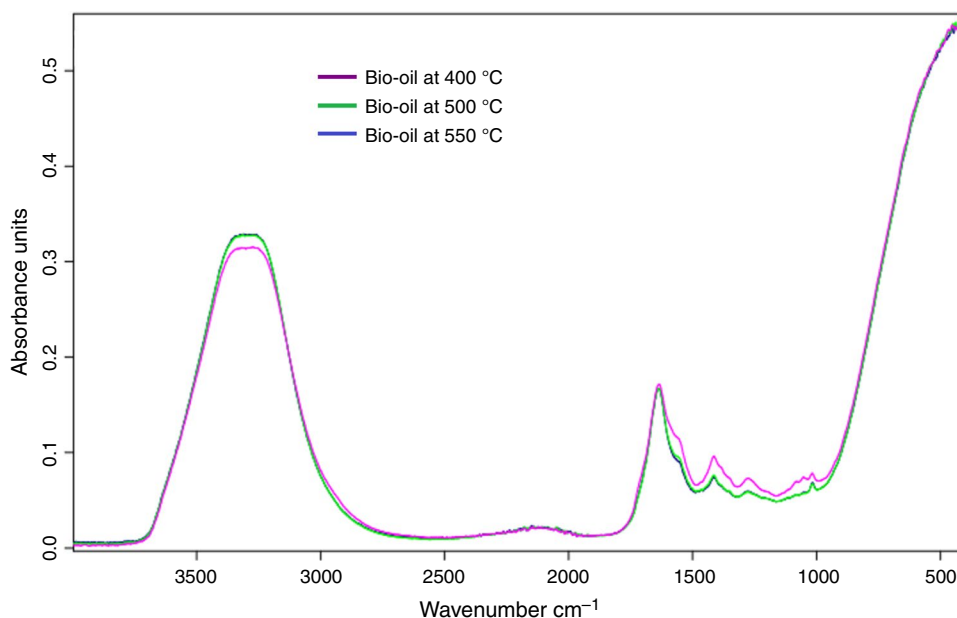


Table 8 FT-IR function groups

Wavenumber/ cm^{-1}	Function groups	Band origin	References
3500–3000	O–H	Alcohol, and phenols	[38]
3000–2500	C–H	Alkanes, and alkenes (Aliphatic)	
1700–1600	C=O	Ketones and aldehydes	[39]
1600–1500	C=C	Olefinic and aromatic	
1200–1000	C–O	Alcohol, phenol, ester, and ether	[40]
700–450	C–H	Aromatic rings	

(2) at 500 °C, and sample (3) at 550 °C. Table 8 presents a rundown of recognizable functional groups. Interestingly, despite differences in sample temperature, the spectra appear similar and share multiple functional groups. The diagram of the FT-IR spectrum can be primarily divided into three prominent peaks. The first peak spans a range between 4000 and 3000 cm^{-1} wavenumber, exhibiting the highest absorbance, ranging between 0.31 and 0.35. Table 8 indicates the presence of alcohol and phenols in this range. Following this, both the blue and purple curves show absorbance levels around 0.18. The final, most pronounced peak appears between 700 and 450 cm^{-1} wavelength. Within this range, the green curve displays the highest absorbance, denoting the presence of aromatic rings. In summary, FT-IR analysis offers a comprehensive means of dissecting the chemical makeup of bio-oil derived from camelthorn plant pyrolysis. By determining the functional groups and patterns in the FT-IR spectrum, critical insights can be obtained into the composition of bio-oil. These findings help optimize pyrolysis processes for enhanced yield and quality.

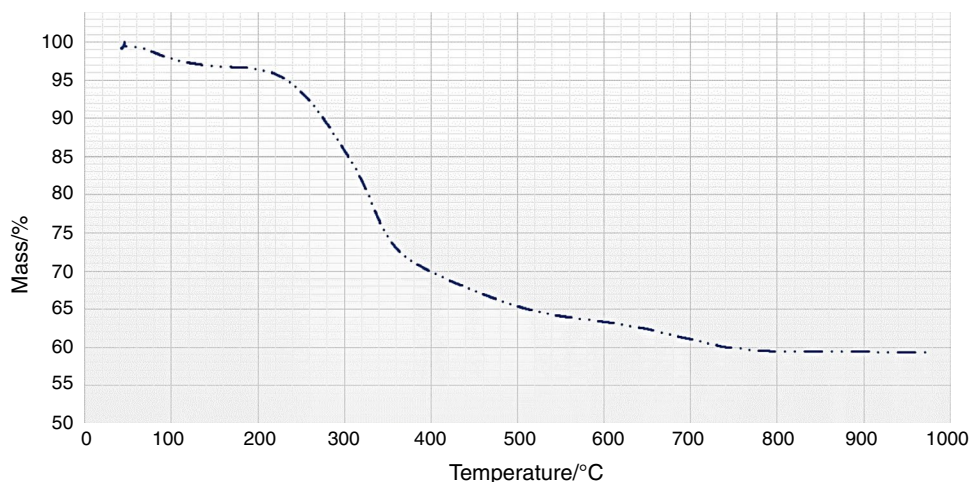
GC–MS analysis offered a detailed identification of specific chemical constituents within the bio-oil. At 400 °C, notable compounds include trichloromethane (CHCl_3), and various oxygenated hydrocarbons like $\text{C}_7\text{H}_{12}\text{O}$, $\text{C}_7\text{H}_8\text{O}_2$, and $\text{C}_7\text{H}_8\text{O}$ were found. These results aligned with the presence of carbonyl and hydroxyl groups detected by FT-IR. The GC–MS results further revealed that phenolic compounds such as phenol, p-cresol, and m-Guaiacol were detected, with varying concentrations according to pyrolysis temperature. At 500 °C, compounds like $\text{C}_7\text{H}_{12}\text{O}_2$ and $\text{C}_9\text{H}_{12}\text{O}_3$ become more prominent, which correlated with the functional groups identified in the FT-IR spectrum. The FT-IR results of persistent functional groups across different pyrolysis temperatures aligned with the GC–MS findings that detail the relative abundances and specific retention times of these compounds. Accordingly, the decrease in trichloromethane content from 20.43% at lower temperatures

to 0.1707% at higher temperatures was paralleled by the diminishing intensity of certain functional group peaks in the FT-IR spectra. This combined analysis highlighted the temperature-sensitive nature of the pyrolysis process demonstrating how variations in temperature influenced both the functional group distribution (as seen in FT-IR) and the specific chemical constituents (as seen in GC–MS). Such detailed insights are crucial for optimizing pyrolysis conditions to enhance the yield and quality of bio-oil, providing a deeper understanding of the chemical transformations occurring during the pyrolysis of camelthorn plants.

Thermogravimetric analysis

The investigation of camelthorn plant pyrolysis was initially undertaken in its initial phases through the utilization of a thermogravimetric analyzer (TGA). Employing the TGA, careful studies were conducted, wherein the continuous recording of sample mass loss was accomplished. The aim of the TGA analysis of camelthorn plant biomass was to study its thermal degradation stages, specifically focusing on the breakdown of cellulose, hemicellulose, and lignin, to gain insights into the processes involved in the generation of bio-oil via pyrolysis. This curve unveils a distinct pattern in the camelthorn biomass: an initial mass reduction attributed to the evaporation of moisture and volatile components, followed by a consistent mass loss indicative of the thermal degradation of the biomass. Throughout this procedure, nitrogen gas was employed as the inert atmosphere, and a heating rate of 10 °C min^{-1} was imposed. The temperature range extended from room temperature up to 970 °C, being held at that point until a state of stability was attained. The thermal stability assessment of the camelthorn plant was executed based on the revelations extracted from the thermogravimetric analyzer. Figure 8 illustrates the thermal degradation of hemicellulose, cellulose, and lignin content, providing a visual representation of these intricate processes.

Fig. 8 TGA analysis



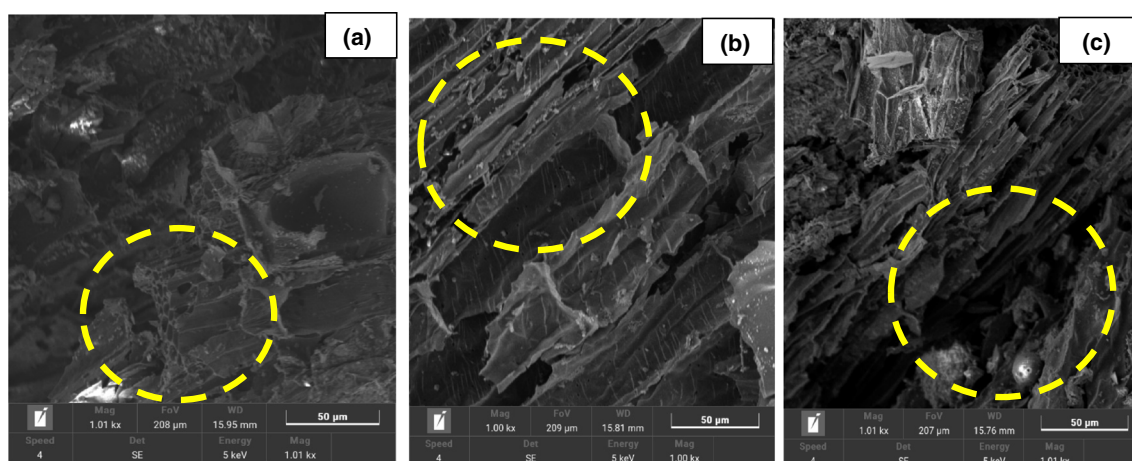


Fig. 9 SEM of biochar samples produced at different temperatures **A** 400 °C, **B** 500 °C, and **C** 550 °C

It presents the TGA outcomes, delineating three primary stages of mass loss. The initial stage involved both water content and volatile organic components removal including the onset of chemical transformations and decompositions due to the applied heat. This stage occurred within the temperature range of 42.39–165.81 °C, taking 4–15 min. Subsequently, hemicellulose, one of the major components of biomass, began to break down into smaller fragments in this phase. This degradation is marked by a continuous, moderate mass loss from 168 to 330.2 °C taking 16 to 33 min. In the third stage, cellulose went to thermal degradation. The breakdown of cellulose into volatile gases and char is responsible for a significant mass loss. Lignin, a complex and rigid component of biomass, experienced degradation at relatively higher temperatures. This stage involved the release of char, tar, and gases like phenols and methoxy compounds. The findings reported by Makkawi et al. [41], who studied the thermal degradation of palm waste, are in good agreement with the results of this study. This knowledge has the potential to develop diverse applications across various industries, underpinning its value in advancing the understanding of this botanical resource.

Surface morphology and elemental analysis

The SEM images in Fig. 9A–C display noticeable distinctions among the biochar samples. The SEM micrographs clearly showed the porous architecture of each resultant biochar, revealing diverse configurations within micropores, macropores, and mesopores. At 400 °C, the biochars collected exhibited an incompletely developed porous structure, as they retained tissue that had not undergone devolatilization. This contributed to less advanced pore formation. In contrast, at 500 °C, the biochar morphology transformed into a honeycomb-like structure, featuring interconnected

cylindrical holes alongside larger openings. The micrographs depict an orderly arrangement of pores across the biochar surface, with a distinct regular pattern of small perpendicular blocks discernible in Fig. 9B. However, at 550 °C, this block pattern underwent disruption, as evidenced in Fig. 9C. The biochars pyrolyzed at 550 °C displayed notable cracks and contractions on their surface due to the elevated temperature. Remarkably, these biochars demonstrated highly porous, hollow, spherical particles characterized by well-structured arrangements in Fig. 9C. The delicacy of their construction was apparent, owing to their slender walls. With an elevation in pyrolysis temperature, the biochars exhibited increased structural order, attributed to a decline in micropore count and a rise in macropore prevalence. These observations align well with findings reported by Elnour et al. [42]

Conclusions

The progressive pyrolysis of the camelthorn plant showed invaluable insights into its thermal decomposition behavior and the intricate composition of the resultant compounds. An array of analytical techniques such as GC–MS, FT-IR, TGA, and SEM assessment were applied. FT-IR spectra indicated the presence of hydroxyl groups, carbonyl compounds, and aromatics, reflecting the evolving chemical composition with increasing pyrolysis temperature. GC–MS analysis corroborated these findings, highlighting temperature-sensitive changes in bio-oil composition, such as the decrease in oxygenated compounds and the increase in aromatic hydrocarbons. The most prominent spectral characteristics were situated within the wavelength range of 700–450 cm^{-1} . The thermogravimetric analysis identified the pyrolysis temperature range, the initiation of thermal degradation, and the energy demand for decomposition. Notably,

the pyrolysis phase was observed at elevated temperature of around 200 °C. Surface morphology analysis using scanning electron microscopy (SEM) illustrated the transformation of biochar structure from less developed porous forms at lower temperatures to well-defined and highly porous structures at higher temperatures. This qualitative assessment underscored the influence of pyrolysis temperature on biochar morphology, indicating potential applications. This holistic knowledge served to optimize pyrolysis protocols, fostering the utilization of camelthorn plant biomass for sustainable energy production and the creation of value-added commodities.

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References

- Yuliansyah AT, Hirajima T, Kumagai S, Sasaki K. Production of solid biofuel from agricultural wastes of the palm oil industry by hydrothermal treatment. *Waste Biomass Valor*. 2010;1:395–405.
- Elhenawy Y, Fouad Y, Marouani H, Bassyouni M. Performance analysis of reinforced epoxy functionalized carbon nanotubes composites for vertical axis wind turbine blade. *Polymers*. 2021;13(3):422.
- Chum HL, Overend RP. Biomass and renewable fuels. *Fuel Process Technol*. 2001;71(1–3):187–95.
- Alanezi AA, Bassyouni M, Abdel-Hamid SMS, Ahmed HS, Abdel-Aziz MH, Zoromba MS, Elhenawy Y. Theoretical investigation of vapor transport mechanism using tubular membrane distillation module. *Membranes*. 2021;11(8):560. <https://doi.org/10.3390/membranes11080560>.
- Williams PT, Nugranad N. Comparison of products from the pyrolysis and catalytic pyrolysis of rice husks. *Energy*. 2000;25(6):493–513.
- Domazetovska S, Strezov V, Filkoski RV, Kan T. Exploring the potential of biomass pyrolysis for renewable and sustainable energy production: a comparative study of corn cob, vine rod, and sunflower. *Sustainability*. 2023;15(18):13552.
- Rakitov Roman, Appel Esther. Life history of the camelthorn gall leafhopper, *Scenergates viridis* (Vilbaste)(Hemiptera, Cicadellidae). *Psyche A J Entomol*. 2012;2012:1–19. <https://doi.org/10.1155/2012/930975>.
- Molaei-Kordabad N, Alizadeh-Salteh S, Ghanbari-Jahromi M, Saber M. In vitro study on anticancer effect of Dodder grown on fennel (*Foeniculum vulgare*) and camelthorn (*Alhagi maurorum*) against human cancer cells lines. *J Herb Med*. 2024;43: 100819.
- Kazemi M, Bezdi KG. An investigation of the nutritional value of camelthorn (*Alhagi maurorum*) at three growth stages and its substitution with part of the forage in Afshari ewes' diets. *Anim Feed Sci Technol*. 2021;271:114762. <https://doi.org/10.1016/j.anifeedsci.2020.114762>.
- Smit HC, Meincken M. Time/temperature combustion profiles of various wood-based biofuels. *Biomass Bioenerg*. 2012;39:317–23.
- Mlambo V, Mould FL, Sikosana JLN, Smith T, Owen E, Mueller-Harvey I. Chemical composition and in vitro fermentation of tannin rich tree fruits. *Anim Feed Sci Technol*. 2008;140:402–17.
- Ngwa AT, Nsahla IV, Bonsi MLK. The rumen digestion of dry matter, nitrogen and cell wall constituents of the pods of *Leucaena leucocephala* and some *Acacia* species. *J Sci Food Agric*. 2002;82(1):98–106.
- Pirasteh-Anosheh H, Parvizi H, Parnian A, Esfahan EZ, Ranjbar G, Bhardwaj A K. Relationship between soil salinity and alkalinity with *Alhagi camelorum* growth in hypersaline and hyperarid environments. *J Arid Environ*. 2022;206:104830. <https://doi.org/10.1016/j.jaridenv.2022.104830>.
- Osman AI, Mehta N, Elgarahy AM, Al-Hinai A, Al-Muhtaseb AAH, Rooney DW. Conversion of biomass to bio-fuels and life cycle assessment: a review. *Environ Chem Lett*. 2021;19:4075–118.
- Chong CT, Mong GR, Ng JH, Chong WWF, Ani FN, Lam SS, Ong HC. Pyrolysis characteristics and kinetic studies of horse manure using thermogravimetric analysis. *Energy Convers Manage*. 2019;180:1260–7.
- Demirbas A, Arin G. An overview of biomass pyrolysis. *Energy Sources*. 2002;24(5):471–82.
- Jeong JY, Yang CW, Lee UD, Jeong SH. Characteristics of the pyrolytic products from the fast pyrolysis of palm kernel cake in a bench-scale fluidized bed reactor. *J Anal Appl Pyrol*. 2020;145: 104708.
- Xiu S, Shahbazi A. Bio-oil production and upgrading research: A review. *Renew Sustain Energy Rev*. 2012;16(7):4406–14.
- Sindhu R, Binod P, Pandey A, Ankaram S, Duan Y, Awasthi MK. Chapter 5-Biofuel production from biomass: toward sustainable development. In: Kumar S, Kumar R, Pandey A, editors. *Current developments in biotechnology and bioengineering*. Amsterdam: Elsevier; 2019. p. 79–92.
- Solantausta Y, Oasmaa A, Sipilä K, Lindfors C, Lehto J, Autio J, Jokela P, Alin J, Heiskanen J. Bio-oil production from biomass: steps toward demonstration. *Energy Fuels*. 2012;26(1):233–40.
- Sutrisno, B., & Hidayat, A. (2016, November). Upgrading of bio-oil from the pyrolysis of biomass over the rice husk ash catalysts. In: IOP conference series: materials science and engineering, IOP Publishing, Vol. 162, No. 1, p. 012014.
- Glaser B, Haumaier L, Guggenberger G, Zech W. The Terra Preta phenomenon: a model for sustainable agriculture in the humid tropics. *Naturwissenschaften*. 2001;88(1):37–41.
- Tripathi M, Sahu JN, Ganesan P. Effect of process parameters on production of biochar from biomass waste through pyrolysis: a review. *Renew Sustain Energy Rev*. 2016;55:467–81.
- Mata TM, Martins AA, Caetano NS. Microalgae for biodiesel production and other applications: a review. *Renew Sustain Energy Rev*. 2010;14(1):217–32.
- Jeong J-Y, Yang C-W, Lee U-D, Jeong S-H. Characteristics of the pyrolytic products from the fast pyrolysis of palm kernel cake in a bench-scale fluidized bed reactor. *J Anal Appl Pyrolysis*. 2020;145:104708. <https://doi.org/10.1016/j.jaap.2019.104708>.
- Maliutina K, Tahmasebi A, Jianglong Yu, Saltykov SN. Comparative study on flash pyrolysis characteristics of microalgal and lignocellulosic biomass in entrained-flow reactor. *Energy Convers Manage*. 2017;151:426–38.
- Gómez N, Banks SW, Nowakowski DJ, Rosas JG, Cara J, Sánchez ME, Bridgwater AV. Effect of temperature on product performance

- of a high ash biomass during fast pyrolysis and its bio-oil storage evaluation. *Fuel Process Technol.* 2018;172:97–105.
28. Al Arni S. Comparison of slow and fast pyrolysis for converting biomass into fuel. *Renew Energy.* 2018;124:197–201.
 29. Ravikumar C, Senthil Kumar P, Subhashni SK, Tejaswini PV, Varshini V. Microwave assisted fast pyrolysis of corn cob, corn stover, saw dust and rice straw: experimental investigation on bio-oil yield and high heating values. *Sustain Mater Technol.* 2017;11:19–27. <https://doi.org/10.1016/j.susmat.2016.12.003>.
 30. Park J, Lee Y, Ryu C, Park Y-K. Slow pyrolysis of rice straw: analysis of products properties, carbon and energy yields. *Biore-sour Technol.* 2014;155:63–70. <https://doi.org/10.1016/j.biortech.2013.12.084>.
 31. Verma M, Godbout S, Brar SK, Solomatnikova O, Lemay SP, Larouche JP. Biofuels production from biomass by thermochemical conversion technologies. *Int J Chem Eng.* 2012;2012:1–18. <https://doi.org/10.1155/2012/542426>.
 32. Jahirul M, Rasul M, Chowdhury A, Ashwath N. Biofuels production through biomass pyrolysis—a technological review. *Energies.* 2012;5(12):4952–5001. <https://doi.org/10.3390/en5124952>.
 33. Shen M-Y, Kuan C-F, Kuan H-C, Ke C-Y, Chiang C-L. Study on preparation and properties of agricultural waste bagasse eco-type bio-flame-retardant/epoxy composites. *J Therm Anal Calorim.* 2021;144:525–38.
 34. Gargoum HM, Muftah SS, Al Shalmani S, Mohammed HA, Alzoki AN, Debani AH, El Shari F, El Barassi I, Meghil SE, Abdellatif AG. Phytochemical screening and investigation of the effect of *Alhagi maurorum* (camel thorn) on carbon tetrachloride, acetaminophen and adriamycin induced toxicity in experimental animals. *J Sci Innov Res.* 2013;2(6):1023–33.
 35. Al-Bukhaiti WQ, Noman A, Qasim AS, Al-Farga A. Gas chromatography: principles, advantages and applications in food analysis. *Int J Agric Innov Res.* 2017;6(1):2319–1473.
 36. Afraz M, Muhammad F, Nisar J, Shah A, Munir S, Ali G, Ahmad A. Production of value added products from biomass waste by pyrolysis: an updated review. *Waste Manag Bull.* 2024;1(4):30–40. <https://doi.org/10.1016/j.wmb.2023.08.004>.
 37. Muley PD, Henkel C, Abdollahi KK, Boldor D. Pyrolysis and catalytic upgrading of pinewood sawdust using an induction heating reactor. *Energy Fuels.* 2015;29(11):7375–85.
 38. Si F, Zhang H, Feng X, Yulong X, Zhang L, Zhao L, Li L. Thermodynamics and synergistic effects on the co-combustion of coal and biomass blends. *J Therm Anal Calorim.* 2024. <https://doi.org/10.1007/s10973-024-13310-5>.
 39. Silva FS, Nascimento SS, Victor A, dos Santos M, da Guarda Souza O. Study of the thermal decomposition of mixtures sugarcane bagasse/titanium dioxide. *J Therm Anal Calorim.* 2023;148(1):37–47. <https://doi.org/10.1007/s10973-022-11583-2>.
 40. Loganathan S, Valapa RB, Mishra RK, Pugazhenth G, Thomas S. Thermogravimetric analysis for characterization of nanomaterials. In: Thomas S, Thomas R, Zachariah AK, Mishra RK, editors. *Thermal and rheological measurement techniques for nanomaterials characterization.* Amsterdam: Elsevier; 2017. p. 67–108.
 41. Makkawi Y, El Sayed Y, Salih M, Nancarrow P, Banks S, Bridgewater T. Fast pyrolysis of date palm (*Phoenix dactylifera*) waste in a bubbling fluidized bed reactor. *Renew Energy.* 2019;143:719–30. <https://doi.org/10.1016/j.renene.2019.05.028>.
 42. Elnour AY, Alghyamah AA, Shaikh HM, Poulouse AM, Al-Zahrani SM, Anis A, Al-Wabel MI. Effect of pyrolysis temperature on bio-char microstructural evolution, physicochemical characteristics, and its influence on biochar/polypropylene composites. *Appl Sci.* 2019;9(6):1149.

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