Environ Res Tec, Vol. 7, Issue. 3, pp. 395–405, September 2024

Environmental Research and Technology
https://ert.yildiz.edu.tr - https://dergipark.org.tr/tr/pub/ert
DOI: https://10.35208/ert.1385026

Research Article

Thermal analysis of St. John's Wort wastes and biochars: A study of combustion characteristics and kinetics

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ARTICLE INFO

Article history
Received: 02 November 2023
Revised: 19 March 2024
Accepted: 22 April 2024

Key words:
Biochar; Biomass; Combustion kinetic; Thermogravimetric analysis

ABSTRACT

St. John's wort, extensively utilized in industries such as food, medicine, and cosmetics, generates substantial biomass waste. Utilizing these wastes is crucial to reducing environmental harm and making an economic contribution. This study aimed to determine the potential of St. John's wort wastes and biochar forms produced from these wastes to be used as solid fuel. In this context, the combustion behavior of the biomass and biochar were determined by thermogravimetric analysis method. Additionally, the Kissenger-Akahira-Sunosa and Flynn-Wall-Ozawa techniques were used to compute the combustion activation energies of these samples. According to the analysis, biomass combustion commenced at approximately 250°C and occurred in two stages, whereas biochar combustion initiated at around 400°C and proceeded in a single stage. Furthermore, over 90% of the mass from both samples was observed to decompose during combustion, with average combustion activation energies ranging between 70.08 and 203.86 kJ/mol for biomass and biochar, respectively. These findings suggest that biomass exhibits more readily combustible characteristics compared to biochar but is less energy efficient. In conclusion, optimizing the biochar production process could enhance its energy efficiency and potentially narrow the performance gap between biomass and biochar. Additionally, further research into alternative methods or additives to improve the energy efficiency of biomass combustion is warranted.

Cite this article as: Koçer AT. Thermal analysis of St. John's Wort wastes and biochars: A study of combustion characteristics and kinetics. Environ Res Tec 2024;7(3)395–405.

INTRODUCTION

Waste solid biomass, which includes various organic materials such as agricultural residues, wood waste, and food waste, is becoming one of the most important environmental and economic problems due to the ever-increasing human population and consumption [1]. When stored in landfills or open dumping sites, these wastes can pose risks to human health and ecosystems by releasing some greenhouse gases that intensify climate change, as well as creating leaks that contaminate groundwater and drinking water [2]. Disposal of these wastes by methods such as incineration is not only economically costly but can also result in the release of gases and ashes that can pollute the air, water and soil [3]. For these reasons, people have researched and developed alternative methods to utilize these wastes. One common technique is composting, which involves the controlled decomposition of organic waste to produce nutrient-rich compost [4]. When waste solid biomass is composted, it reduces its volume, prevents methane emissions, and produces a valuable soil amendment. Compost can enhance soil fertility, improve water retention, and reduce the need for chemical fertilizers, hence providing economic benefits for agriculture [5]. Additionally, waste solid bio-

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Published by Yıldız Technical University Press, İstanbul, Türkiye

mass can be used as feedstock for the production of bio-based products. Technologies such as anaerobic digestion, pyrolysis and bio-refineries can convert biomass waste into biogas, biochar, bio-based polymers, and biochemical [6]. This facilitates the shift towards a circular economy, where waste is converted into valuable resources, minimizing waste disposal and reducing reliance on non-renewable resources. These techniques not only mitigate environmental impacts but also provide economic benefits, including renewable energy generation, improved soil fertility, and the creation of job opportunities. It is crucial for governments, industries, and individuals to embrace these techniques and promote sustainable waste management practices to safeguard the environment and sustain economic growth [7].

One of the most widely used methods for the utilization of waste solid biomass is biochar production via pyrolysis. Pyrolysis is a thermal decomposition process that involves the breakdown of organic materials at high temperatures in the absence of oxygen. This process is commonly used to convert biomass into valuable by-products such as bio-oil or bio-crude, syngas and biochar [8]. Biochar, a solid carbon-rich residue, is one of the primary outputs of pyrolysis. It is characterized by its high surface area and porosity, attributes that contribute to its remarkable water-holding capacity and nutrient retention capabilities in soils. These properties make biochar an invaluable tool for soil improvement and sustainable agriculture practices [9]. Moreover, biochar exhibits exceptional thermal stability, enabling it to persist in soils for extended periods, effectively sequestering carbon and mitigating climate change as a long-term carbon sink [10]. Its presence in the soil not only enhances soil fertility but also promotes microbial activity, fostering a healthier and more resilient ecosystem [11]. Another area where biochar is widely used is in environmental applications. Biochar, either directly or in the form of activated carbon, is effectively used to remove various pollutants from wastewater [10]. In addition, biochar can also be used in combustion and gasification applications and is recommended as a sustainable alternative to traditional fossil fuels as it contributes to a significant reduction in greenhouse gas emissions [11]. Furthermore, biochar's structural integrity make it an attractive option for construction materials, providing a sustainable solution for building materials and contributing to the development of eco-friendly infrastructure [5]. A wide range of biomass feedstocks can be used for production of biochar by pyrolysis, including but not limited to agricultural residues, forest biomass, energy crops, and industrial waste [9].

One of the most intensive uses of biochar is its use as a source in combustion systems. In this context, in order to increase the combustion efficiency of biochar and to use them more effectively in combustion systems, it is very important to determine their combustion behavior, to examine their combustion mechanisms and to determine their combustion kinetics [11]. Thermogravimetric method is an effective method used extensively for this purpose. This method allows for the investigation of solid fuel combustion behavior and processes as well as the calculation of kinetic parameters utilizing various mathematical models and methodologies [12]. Numerous investigations on the combustion processes of biomasses and the biochar generated from these biomasses have been conducted recently. For instance, in the prior work, the thermogravimetric method was used to examine the combustion of waste biomass (*Aloe vera*) and biochar. The activation energy values of the two materials were determined to be 285 kJ/mol and 150 kJ/mol, respectively [11]. In another study, *Ulva lactuca* seaweed's and its charcoal form's combustion activation energies were found to be around 261 kJ/mol and 146 kJ/mol, respectively [13]. Apart from these, studies on the combustion of biochar produced from different materials such as orange peel [14], bamboo [15] and woody [16] are available in the literature.

This study aims to figure out the combustion characteristics of St. John's wort (*Hypericum perforatum*) plant wastes remaining after extraction and the biochars produced from them, to calculate the combustion kinetics parameters and to compare biomass with biochar in this context. St. John's wort is a medicinal plant known for its intriguing properties and numerous potential uses. In the pharmaceutical sector, it is utilized for the production of herbal remedies, including capsules, tablets, and tinctures, which are commonly used to treat depression and associated symptoms [17]. The plant is also used in the cosmetic industry, where it is incorporated into skincare products such as creams, oils, and lotions due to its potential skin-soothing and healing properties [18]. The demand for St. John's wort products has increased in recent years, driven by a growing interest in natural remedies and alternative medicine. Therefore, it can be said that the waste potential of this plant is quite high. When the literature is examined, although there is a study on the pyrolysis of St. John's wort plant and the characterization of the products released by the pyrolysis reaction [19], there is no study on the combustion of these plant wastes and char produced from them. When considered in this context, the novelty of the present paper lies in its focus on exploring the combustion characteristics of St. John's wort plant wastes and the biochars derived from them, filling a gap in the literature regarding the combustion behavior of this particular biomass waste.

MATERIALS AND METHODS

Sample Preparation

St. John's wort plant samples were purchased from a local vendor in İstanbul, Türkiye. 100 grams of dry plant samples were ground into small pieces and then added to 1 L of distilled water and extracted by boiling for about 30 minutes. The suspension obtained after extraction was separated with filter paper and the remained solid pulp was dried in a furnace at the temperature of 70 °C for 1 night. The dried samples were ground again and stored in a desiccator for use in experiments of characterization, production of biochar and combustion.

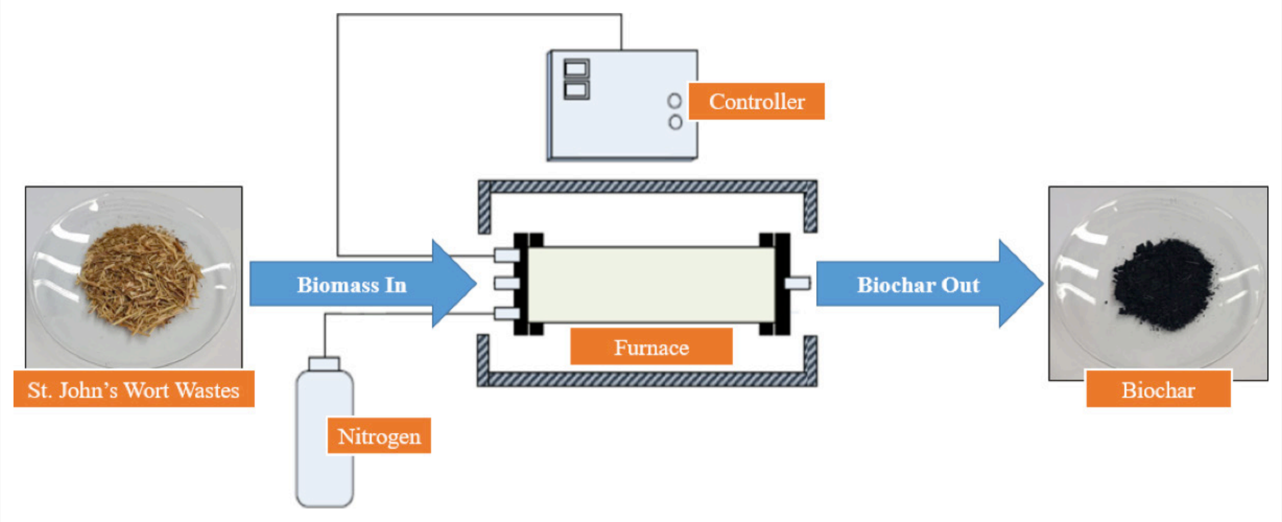

Figure 1. Scheme of biochar samples preparation.

The manufacture of biochar from waste biomass was done in a split furnace (Protherm ASP 11/100/500) with a diameter of 0.10 m and dimensions of 0.51 m × 0.40 m × 0.50 m, according to the process outlined by Koçer and Özçimen [13]. The parameters for the biochar synthesis process were determined to be 400 ˚C, 20 ˚C/min of heating, 30 minutes of retention, and 200 mL/min of nitrogen flow. The split furnace was filled with around 20 g of dried and ground biomass samples, and nitrogen gas was introduced for 15 minutes to remove oxygen. The produced biochar samples were removed from the split furnace and stored for characterization and combustion following the thermal reaction and cooling. The diagram showing the biochar production stages is shown in Figure 1.

Characterization Analyses

Thermal, structural, and proximate analyzes were used to characterize the extracted biomass samples and their biochars. The thermogravimetric analysis (TGA) instrument TA Instruments SDT Q600 was utilized for the thermal analyses of the raw biomass and biochar samples. In this article, five milligrams (mg) of dried samples were placed in an alumina crucible and heated in a dry air environment to a temperature of 800 ˚C, with three different heating speeds (10, 20 and 40 ˚C/min). At 40 mL/min, the dry air flow rate was kept constant. The procedures outlined in Lu and Chen [20] were used to calculate the values of ignition (Ti) and burnout temperature (Tb).

The proximate examination of the biomass and biochar revealed the samples' ash, moisture, volatile matter, and fixed carbon contents. The moisture, volatile matter (VMC), and ash content (AC) of the biomass were determined using a thermogravimetric analyzer in accordance with ASTM standards E 871, E872, and E 1755, in that order. Fixed carbon (FCC) content of biomass was determined by difference [21]. The following Eqs. (1) provided in Parikh et al. [22] were used to compute the higher heating values (HHV) of these samples:

$$HHV=0.3536FCC+0.1559VMC-0.0078AC \quad (1)$$

The elemental compositions of raw biomass and its biochar form were determined using the following equations based on proximate analysis results [23, 24]:

$$C\ (\%)=-35.9972+0.7698VMC+1.3269FCC+0.3250AC \quad (2)$$

$$H\ (\%)=55.3678-0.4830VMC-0.5319FCC-0.5600AC \quad (3)$$

$$O\ (\%)=223.6805-1.7226VMC-2.2296FCC-2.2463AC \quad (4)$$

$$N\ (\%) = 100 - (C + H + O + AC) \quad (5)$$

Kinetic Theory

Model-free kinetic approaches are most frequently used to pyrolysis and combustion kinetics, as they offer an approximate activation energy estimate based on isothermal and non-isothermal observations [25]. Two of these techniques, the Flynn-Wall-Ozawa (FWO) method and the Kissenger-Akahira-Sunosa (KAS) method, are expressed as follows:

- KAS method [26] expressed as follows:

$$\ln\left[\frac{\beta}{T^2}\right] = \ln\left[\frac{A.E}{R.g(\alpha)}\right] - \frac{E}{R.T} \quad (6)$$

where the activation energy (E) value is determined from the slope of a plot of ln(β/T^2) against 1/T.

- FWO method [27, 28] expressed as follows:

$$\ln\beta = \ln\left[\frac{A.E}{R.g(\alpha)}\right] - 5.331 - 1.052\frac{E}{R.T} \quad (7)$$

where the activation energy (E) value is determined from the slope of a plot of ln(β) against 1/T.

In these equations, β represents the heating rate (K/min), T denotes the temperature (K), A denotes for the frequency factor (1/s), R represents the universal gas constant (8.314 J/mol·K), and α expresses the conversion ratio.

RESULTS AND DISCUSSION

Properties of St. John's Wort Wastes

Table 1 presents the characterization results of both the biomass and biochar samples obtained in this study, along

Table 1. Characterization of St. John's wort plant waste and biochar samples

	Units	Biomass	Biochar	Biomass*	Biochar*
Volatile matter	%	74.04	12.59	69.7	–
Fixed carbon	%	22.81	81.28	17.6	–
Ash	%	3.15	6.13	3.8	–
C	%	52.29	83.58	45.6	79.6
H	%	5.71	2.62	6.4	2.48
O	%	38.21	7.00	45.5	15.12
N	%	0.64	0.71	1.8	2.06
HHV	MJ/kg	19.58	30.66	16.52	27.84

*: Ateş et al. [19].

with a comparative analysis against findings from existing literature. In this table, the effect of the carbonization process on the biomass content is quite clear. Volatile matter content decreased from 74.04% to 12.59% with the carbonization process, while fixed carbon content increased from 22.81% to 78.41%. The ash content in the biomass did not change during the carbonization process, but the percentage of ash content mathematically increased as the total mass decreased. When the change in elemental composition was examined, it was seen that C and N content increased with the carbonization process, but H and O content decreased. As expected, the increase in C content was due to the transformation of the biomass into a carbon-rich char-like structure. The decrease in H and O content can be attributed to the progressive dehydration reactions and the release of oxygen and hydrogen containing volatiles [29]. The increase in N content can also be attributed to the N content found in non-volatilized structures resistant to thermal degradation and this is supported by studies in the literature [30, 31]. When the higher heating values are compared, it has seen that this value of biochar is higher. This is because the increase in higher heating value is due to the increase in the carbon content of the biochar formed as a result of the pyrolysis reaction, thus leading to an intensification of the mass-energy density [29].

Comparison of the data from the study conducted by Ateş et al. [19] reveals that the biomass samples exhibit similar proximate and elemental compositions, albeit with minor discrepancies.

Despite the utilization of the same plant species in both studies, the reason for these small differences can be attributed to the fact that the biomass used in this study was extracted. Upon comparing the biochar samples, it can be seen that other components are similar to each other, except for O and N contents. The higher O and N contents reported by Ateş et al. [19] could potentially be attributed to the extraction process employed in this study, which may have led to the removal or decomposition of certain N- and O-containing components under the influence of extraction temperatures.

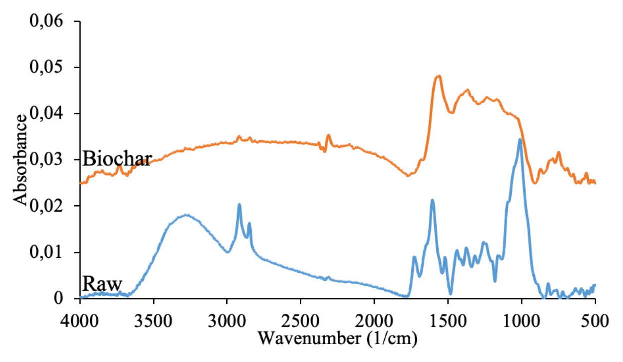

Figure 2. FTIR spectrum of samples.

The FTIR spectra of raw biomass waste and their biochar forms are shown in Figure 2. The broad absorption band at 3300 cm^{-1} seen in the spectrum of raw biomass indicates OH stretches due to moisture and alcohol content of the materials [32]. Peaks at 2920 and 2852 cm^{-1} are also due to CH and CH$_2$ stretching [33], while peaks at 1730 and 1600 cm^{-1} indicate C=O stretch and NH$_2$ deformation, respectively. Peaks at 1250 and 1025 cm^{-1} represent the pyranose and furanose rings [34–36]. Peaks at 1570, 1400 and 850 cm^{-1} seen in the FTIR spectra of biochar are due to C=C stretching of hemicelluloses, C-H deformation in cellulose and hemicelluloses and C=C stretching alkene vinylidene, respectively [37]. The effects of the carbonization process on biomass can be seen quite clearly in this figure. Especially the OH, CH and CH$_2$ stresses in the biomass were destroyed during biochar formation. In addition, with this process, the peaks between 1800–1600 cm^{-1} merged and shifted to the 1550 cm^{-1} region. Furthermore, the peak at 1000 cm^{-1} due to the carbohydrate content of the biomass was also reduced as expected.

The SEM images of St. John's wort waste and its biochar form at the magnification of 1000x are shown in Figure 3. In the SEM images of raw biomass waste (Fig. 3a), there are small non-porous pieces and long thin rod-shaped pieces. Due to the degredation of the structure and the movement of mass away from it as a result of the temperature increase during the carbonization reaction, pores and cracks have formed in the structure of the biochar, as depicted in Figure 3b. Con-

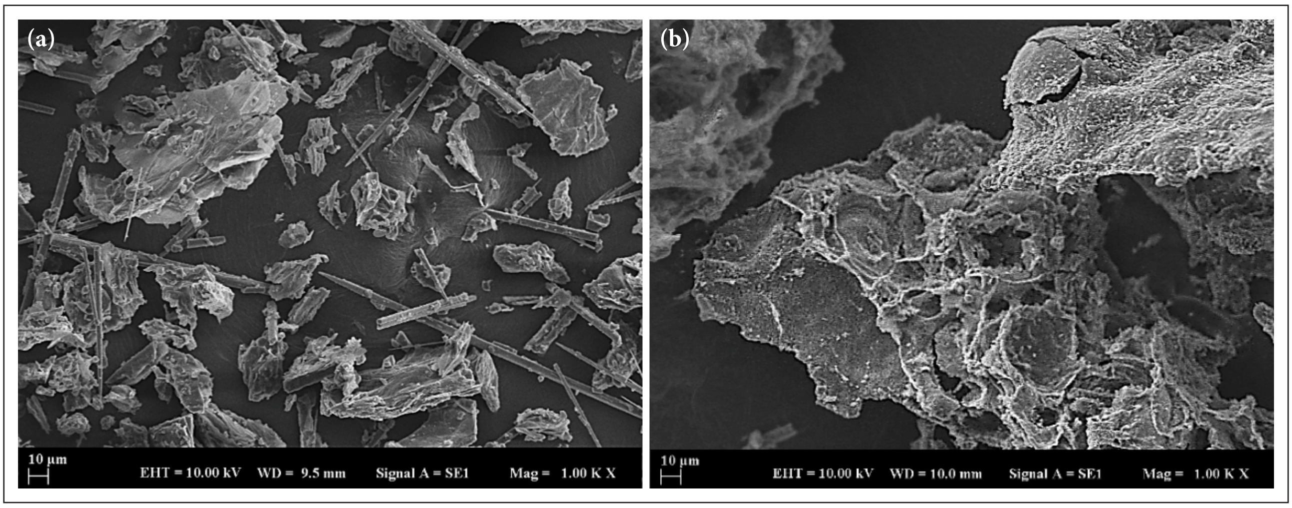

Figure 3. SEM images at 1000 x magnifications **(a)** St. John's wort waste, **(b)** biochar.

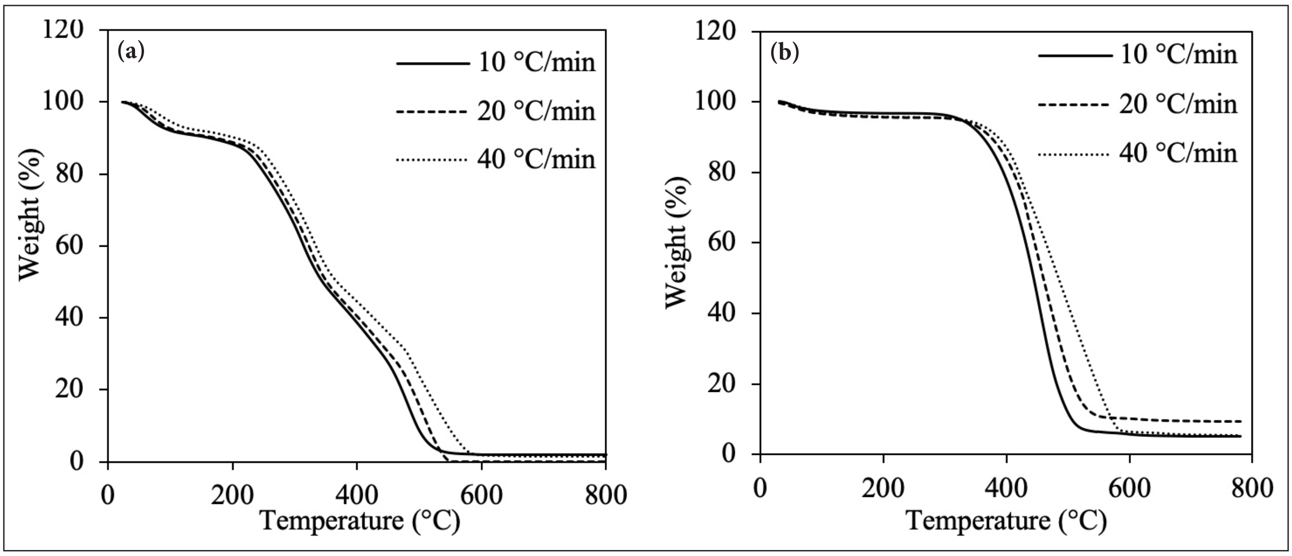

Figure 4. TG curves of combustion of **(a)** Raw biomass, **(b)** Biochar.

sequently, it can be concluded that the porosity and surface area of biochar are higher than those of biomass [38]. When compared to the SEM image of biochar derived from St. John's wort biomass at a temperature of 500 °C as provided in the study by Ateş et al. [19], it can be said that the pores and cracks in the structure are similar to those in this study.

Thermal Behaviours of Samples

The combustion thermograms of St. John's wort wastes and their biochars are shown in Figure 4 and the data in this figure are shown in Table 2. According to this figure, it can be seen that all samples burned at a rate of approximately 90% to 99% and that this process occurred in 2 temperature zones. In the first zone, it can be said that the relative humidity or the moisture adsorbed from the air is removed as the temperature increases up to about 175 °C for each material [39]. The mass losses in this region are around 10% for raw biomass and around 5% for biochar. The second region was realized differently for raw biomass and biochar. For raw biomass, this zone was realized in two stages. The first one took place between about 200 and 400 °C and in this zone the proteinic, cellulosic and hemicellulosic contents of the materials were burned [13]. The second stage took place between 400 and 550 °C, where char remaining after devolatilization of the samples was burned [40].

When the combustion thermograms of biochar samples are examined, it has seen that the main mass loss is in the second region and this loss occurs in a single stage. The reason for this situation is that structures such as protein and carbohydrate in the biomass are degraded during biochar production and removed from the char [13]. The mass loss in this region was measured to be approximately 85–90%. The main reason for such high values can be attributed to the low ash content of the biomass and consequently of the biochar. Another conclusion that can be drawn about the combustion reactions of raw biomass and biochar is that the second zone of biomass combustion starts earlier than that of biochar. The reason for this is that the easily ignitable volatiles in the biomass are removed from the char structure during biochar production [11].

Table 2. Thermal degredation characteristics

Heating rate (°C/min)	Parameters	Biomass		Biochar
		200–400 °C	400–550 °C	200–650 °C
10	T_i	249	–	387
	T_{max}	311	478	447
	T_b	–	512	492
	WL	44.37	42.76	90.17
20	T_i	254	–	391
	T_{max}	322	490	453
	T_b	–	540	524
	WL	44.15	47.10	85.33
40	T_i	261	–	396
	T_{max}	328	494	462
	T_b	–	568	570
	WL	43.63	45.32	89.17

T_i: Ignition temperature; T_{max}: Temperature at maximum loss rate; T_b: Burnout temperature; WL: Weight loss.

Table 3. The combustion activation energy values of raw biomasses

α	Raw				Biochar			
	KAS		FWO		KAS		FWO	
	E_a (kJ/mol)	R^2	E_a (kJ/mol)	R^2	E_a (kJ/mol)	R^2	E_a (kJ/mol)	R^2
0.1	97.33	0.990	100.86	0.991	183.73	0.997	185.14	0.997
0.2	98.31	0.957	102.24	0.963	203.03	0.983	203.86	0.984
0.3	97.89	0.929	102.21	0.940	201.23	0.999	202.44	0.999
0.4	88.65	0.930	93.77	0.943	166.44	0.976	169.64	0.979
0.5	57.35	0.897	64.50	0.923	139.17	0.960	143.97	0.966
0.6	42.68	0.880	51.14	0.920	117.89	0.953	123.96	0.961
0.7	43.44	0.862	52.48	0.909	102.82	0.947	109.86	0.958
0.8	48.55	0.847	57.79	0.896	93.87	0.946	101.59	0.958
0.9	56.53	0.918	65.86	0.943	92.88	0.937	100.95	0.952
Ave.	70.08		76.76		144.56		149.05	

Combustion Kinetics

In order to determine the combustion kinetic parameters of raw St. John's wort waste and biochar, the non-isothermal curves of KAS and FWO methods were shown in Figure 5. Based on the findings from Figure 5, the values of the combustion activation energy and the regression coefficients of the samples were computed and are shown in Table 3. When the combustion activation energy values of St. John's wort calculated by the KAS method were examined, it was seen that these values varied between 42.68 kJ/mol and 98.31 kJ/mol. When the regression coefficients are examined, it can be said that the coefficients except for the conversions of 0.7 and 0.8 are within the acceptable range and the regression coefficients of the conversions 70% and 80% are slightly below the limit. All of the regression coefficients calculated with FWO were found to be within the acceptable range, and accordingly, it can be concluded that this method is more suitable for determining the combustion kinetics of St. John's wort waste. Using the FWO method, activation energy values were calculated between 51.14 kJ/mol and 102.24 kJ/mol. When studies on combustion kinetics in the literature are examined, it is noted that a large number of biomass types are used as raw materials. For example, Lopez et al. [41] used the Vyazovkin and Ozawa-Flynn-Wall techniques to assess the microalgae and corn blends' combustion kinetics and computed the activation energy value, which came out to be around 171.5 kJ/mol. According to Koçer and Özçimen [13] *Ulva lactuca* macroalgae burned in two phases, with activation energy levels of around 295 kJ/mol and 225 kJ/mol in each. Yorulmaz and Atimtay [42] calculated the combustion kinetics of waste wood samples between 123–136 kJ/mol using the Coats-Redfern method, while Gao et al. [43] determined the combustion activation energy of waste wood as 184.2 kJ/mol using the Broido method.

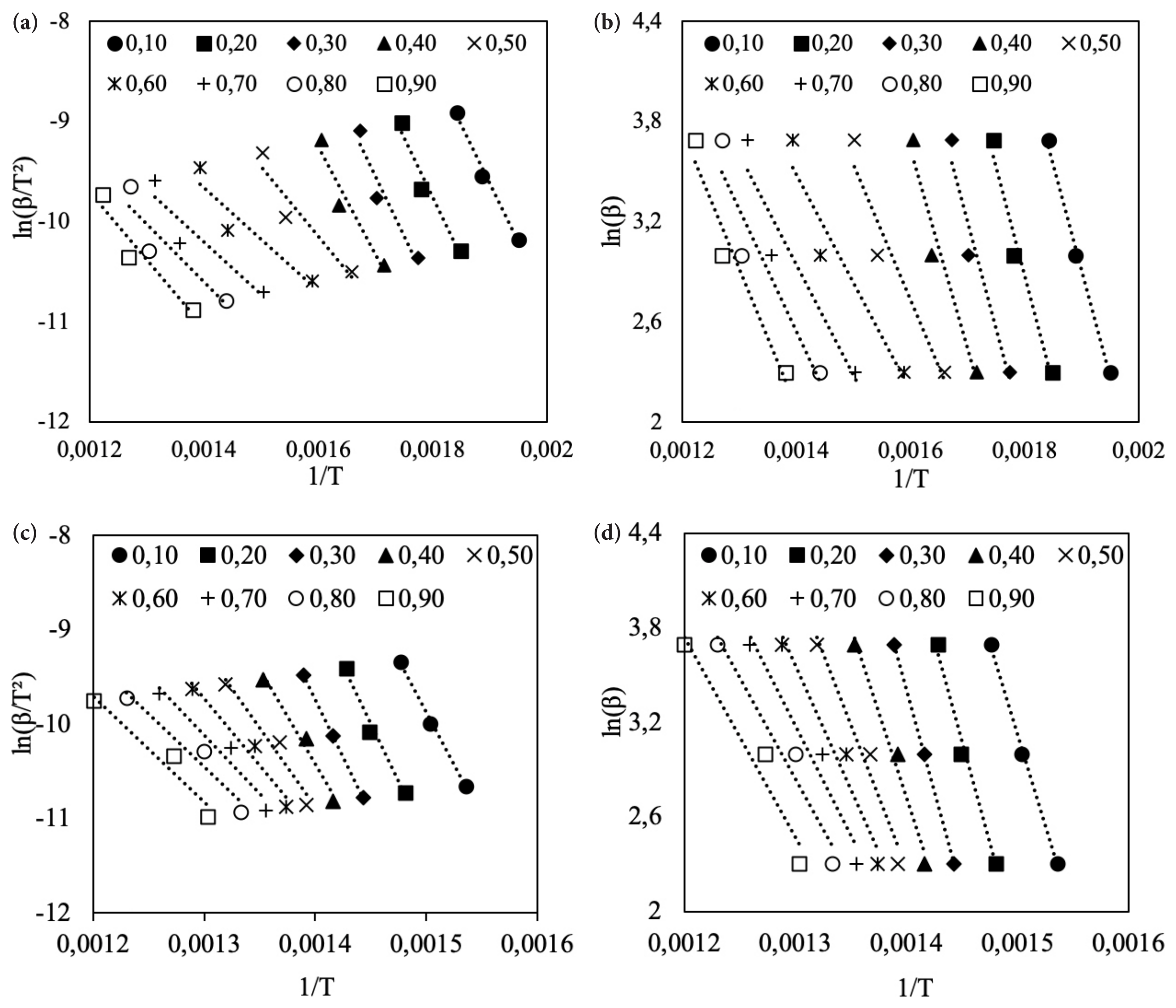

Figure 5. **(a)** Raw biomass KAS, **(b)** Raw biomass FWO, **(c)** Biochar KAS and **(d)** Biochar FWO.

The activation energy values determined by both techniques exhibit a rising trend up to 20% conversion and a decreasing trend between 20% and 60% when the combustion activation energies of St. John's wort are studied. After the conversion of 60%, activation energy values tended to rise once again. When the rates of change in activation energies were analyzed, it was observed that there was no significant change up to 30% conversion, but there was a decrease of approximately 30 kJ/mol especially between 40% and 50% conversion rates. These findings indicate that the biomass's proteinic, cellulosic, and hemicellulosic components were burnt to a 60% conversion rate, after which point the char-like structure that resulted from devolatilization was burned. The activation energy estimates tended to rise after 60% conversion because the char structure is considerably harder to burn.

The average combustion activation energy values of biochar samples were calculated to be approximately 150 kJ/mol, respectively. Regression coefficients higher than 0.9, like those of biomass, indicate that these methods can be used to determine the combustion kinetic parameters of these biochar samples. When the studies in the literature in which the combustion kinetics of biochar are calculated, it is seen that there are different results according to the biomass used and the methods applied. Koçer and Özçimen [13] reported that the average combustion activation energy values of biochar produced from *Ulva lactuca* macroalgae were 146.61 kJ/mol and 140.81 kJ/mol using KAS and FWO methods. Islam et al. [44] calculated the average combustion activation energy of Karanj fruit hulls biochar as 62.13 kJ/mol and 68.53 kJ/mol using KAS and FWO methods. Wang et al. [45] used Random Pore Model and Volume Model approaches for combustion kinetics of Palm Kernel Shell Biochar and calculated the activation energy values as 113.3 kJ/mol and 116.6 kJ/mol. Yu et al. [46] determined the average combustion kinetic energy of pine sawdust biochar as approximately 200 kJ/mol by Friedman Friedman differential isoconversional method.

When the behavior of the activation energy values according to the conversion rate is examined, it can be said

Table 4. Activation energy values and regression coefficients in some studies

Sample	Methods	Results	References
Pine	DAEM	E_a: 111.41–208.62 kJ/mol	[40]
		R^2: 0.906–0.995	
Corn straw		E_a: 97.58–189.13 kJ/mol	
		R^2: 0.906–0.999	
Seaweed (*U. lactuca*)	KAS	E_a: 296.97–225.17 kJ/mol	[13]
		R^2: 0.980–0.996	
	FWO	E_a: 292.39–216.73 kJ/mol	
		R^2: 0.979–0.996	
Seaweed (*U. lactuca*) biochar	KAS	E_a: 146.61 kJ/mol	
		R^2: 0.938–0.990	
	FWO	E_a: 140.81 kJ/mol	
		R^2: 0.943–0.992	
Sugarcane bagasse	Friedman	E_a: 8.17–275.48 kJ/mol	[50]
		R^2: -	
	FWO	E_a: 11.04–88.56 kJ/mol	
		R^2: -	
	KAS	E_a: 3.39–78.28 kJ/mol	
		R^2: -	
Microalgae (*C. pyrenoidosa*)	Vyazovkin	E_a: 65.15 kJ/mol	[51]
		R^2: -	
Palm kernel shell biochar	Random pore model	E_a: 113.3 kJ/mol	[45]
		R^2: 0.999	
	Volume model	E_a: 116.6 kJ/mol	
		R^2: 0.999	
Pine sawdust	KAS	E_a: 212.39 kJ/mol	[52]
		R^2: 0.996–0.999	
	FWO	E_a: 212.66 kJ/mol	
		R^2: 0.996–0.999	
St. John's wort	KAS	E_a: 70.08 kJ/mol	This study
		R^2: 0.847–0.990	
	FWO	E_a: 76.76 kJ/mol	
		R^2: 0.896–0.991	
St. John's wort biochar	KAS	E_a: 144.56 kJ/mol	
		R^2: 0.937–0.999	
	FWO	E_a: 149.05 kJ/mol	
		R^2: 0.952–0.999	

that the activation energy values decrease continuously after 20% conversion for St. John's wort biochar. At these conversion levels, the activation energy values are maximum, which indicate the highest barrier to the combustion compared to that of other conversion degrees [47]. After these conversion levels, the combustion of the fixed carbon in the structure of biochars started and continued until 90% conversion. The porous structure of biochar also facilitated combustion as it increased the contact surface with oxygen [48]. Due to the decrease in fixed carbons in the structure of biochar over time and ash content, activation energy changes at high conversion levels decreased [49]. When the studies on the combustion of biochar or similar materials in the literature are examined, it has seen that similar results are obtained. For example Islam et al. [47] and Islam et al. [44] reported that activation energy values decreased continuously with increasing conversion rate in their studies investigating the combustion of hydrochar and biochar produced from Karanj fruit hulls, respectively. Gao and Li [49] stated that the combustion activation energy values of Coal gangue continuously decreased until about 80% conversion; after 80% conversion, the activation energy increased due to the combustion of fixed carbon content and ash content. Studies on the combustion kinetics of some biomasses and biochar in the literature are summarized in Table 4.

CONCLUSION

The thermal behavior of St. John's wort wastes and their biochars in dry air was investigated by thermogravimetric analysis and the combustion activation energies were determined using KAS and FWO methods. The combustion behavior of raw biomass and biochars after moisture content removal was different. While the combustion of raw biomass occurred in two stages (combustion of biomolecules and char remaining after devolatilization) between approximately 150 °C and 550 °C, the combustion of biochar in this temperature range occurred in one stage (combustion of char structure). The average activation energy values of St. John's wort wastes in this temperature range were calculated as 70.08 kJ/mol and 76.76 kJ/mol by KAS and FWO methods, respectively, while the average combustion activation energy values of biochar wastes in this temperature range were calculated as 144.56 kJ/mol and 149.05 kJ/mol, respectively. Based on an evaluation of the study's results, it can be concluded that these biomasses and their biochar forms can be added to fuels like coal or utilized directly in combustion processes because of their low ash content. This approach will optimize the utilization of these very promising wastes and improve the efficiency of fuels such as low quality coal.

ACKNOWLEDGEMENTS

The author would like to thank Emre Karaduman who provided the samples.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

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