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Research Article

Production of solid fuel with torrefaction from agricultural wastes

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Abstract

In this study, it was aimed to produce solid fuel by applying torrefaction process to agricultural wastes, left in the field (usually left to decay) after harvest or post-cultivation period. An eggplant stalk left in the field as an agricultural waste after production period was used in the study. The torrefaction process was applied to the original plant parts cut in certain lengths, and also to the pellets prepared from the same plant. The torrefaction experiments were performed in a pyrex glass reactor placed inside a vertical cylindrical refractory chamber, through which resistance wires are passed. The torrefaction process was performed in N₂ atmosphere at the operation temperatures of 220, 260 and 300°C. The proximate and elemental analyses of the solid product were performed. Besides, the energy yield was determined by measuring the higher heating values (HHV) of the original sample and solid product. Depending on torrefaction temperature it was determined a decrease in the solid product yield, an increase in the yields of liquid and gas products. While the volatile matter content of the solid product was decreased, it was found that the rate of fixed carbon increased. It was also determined that elemental carbon ratio increased and oxygen ratio decreased as a result of the torrefaction process. It was detected that the higher heating value of the biomass increased with rising torrefaction temperature and 65.58% of the energy that contained has been maintained at severe (300°C) torrefaction conditions.

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1. Introduction

Biomass has recently caught great attention as an energy resource. It is estimated that biomass which is a renewable and carbon neutral energy resource will have a significant role in the energy production in the future. 10% of world total energy consumption and 78% of total renewable energy consist of biomass [1,2]. However, this is lower than expectations considering vast research on biomass energy, oriented to conversion of many varieties of them into substitute fuels for oil and coal. Currently, reducing the effects of global climate change and minimizing environmental consequences of fossil fuel-dependent industry, use of renewable sources is still a crucial option for energy supply.

Biomasses can be broadly classified as woody and non-woody types of materials. Woody biomasses are usually obtained from forestry and wood industry while non-woody biomasses are mostly generated from agricultural actions [3]. For most biomasses a generic term of Lignocelluloses are used to refer main plant constituents which form a complex matrix. For example, woody tissues of land plants are composed of cellulose as

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the major component (30-40%) of cell walls, in turn hemicelluloses (25-35%) and lignin (12-30%). These percentages reflect variable compositions of different biomasses. Considering vast types and varieties of plants, lignocelluloses comprise huge variety of materials with distinctive physical and chemical characteristics [4].

Agricultural wastes are one of the important biomass resources; because they are in an excessive amount and their usage in fuel production does not affect the food production. A lot of agricultural wastes are not evaluated and they are accumulated in open areas and cause to air pollution. High moisture content, low heat value, high volume and low bulk density make difficult to use these wastes as fuel. Many biomass improvement (transformation) methods have been developed to decrease these problems. These methods are gasification, pyrolysis, anaerobic decomposition, fermentation and transesterification. Torrefaction process applied for the solid fuel production is also one of these methods [5].

Torrefaction is the low temperature pyrolysis. The main purpose in the torrefaction process is to decrease the humidity of the biomass and increase its heat value. Biomass can be converted into more uniform solids (biochar) by torrefaction [6-8]. During torrefaction of biomasses, majority of hemicelluloses and some fraction of cellulose decompose by dehydration, deoxygenation and dehydrogenation reactions [9]. The contents of low-energy H-C and O-C bonds are decreased, whereas the content of high-energy C-C bond is increased [10,11]. These changes produce a more uniform, reactive, easy to grind and hydrophobic biomass with reduced O/C and H/C ratios and increased energy density [12-14]. The humidity ratio of the biomass to which torrefaction has been applied is very low. For this reason, it is seen that it ignites in a short time [15]. Also, it has been detected that because the volatile compounds are separated, less smoke has occurred and it has burnt in a longer period of time due to the fact that fixed carbon ratio has increased [16].

The parameters effecting biochar yields or mass losses have been studied extensively. Torrefaction temperature was found to be more effective than duration time and woody biomasses gave more amounts of solids compared to agricultural biomasses [17].

The eggplant is a cultigen, grown yearly in warm climates, and is in the shape of a small tree in tropical climates. The eggplant, which is largely consumed in our country, is produced especially in southern regions with hot climate. The aim of the study is providing for especially woody stalks and branches of the eggplant plant, left in the field at the end of the cultivation season, to be converted into a utilizable solid fuel through torrefaction process.

2. Material and Method

Eggplant stalks (ES) used in the study were supplied from Elmapınarı village in the city of Elazığ. At the end of the production season, the remaining eggplant plant residues were collected and dried in the laboratory atmosphere. A part of the dried sample was grinded and sieved. Grains in the dimension of <100 mesh was separated for usage in the proximate and ultimate analyses and pellet preparation. ASTM standards (ASTM D-3174 for the ash, ASTM D-3175 for the volatile substance) were used for the proximate analysis of the samples. Proximate analysis was conducted both on the original sample and the samples subjected to the torrefaction process. Tests were repeated for at least three times to check the precision and certainty of the proximate and elemental analysis results and the data showing a deviation higher than $\pm 5\%$ of the average value were not taken to the scope to ensure the repeatability of the experimental data. Elemental analyses were conducted with LECO (CHNS-932) Elemental Analysis Device. High heat values (HHV) were determined with Julius Peters I Berlin21 adiabatic calorimeter.

Pellet was prepared from grains in the dimension of <0.150 mm using a hydraulic press. For this, 5 tones/cm^2 of pressure was applied to about 1 ± 0.05 g sample for 30 s, accordingly, pellets with 13mm diameter, and 5mm height were obtained. Besides, approximately 3 and 6 cm long bars, similar to each other, were cut from dry sample, and they were used in the torrefaction experiments.

2.1. Torrefaction

Torrefaction experiments were carried out in the system shown in Fig. 1 System consists of a vertical refractor chamber with 45 mm inner and 115 mm outer diameter and 105 mm height and through which resistance wires were placed and a pyrex glass tube reactor with the diameter of 35 mm and length of 150 mm placed inside the chamber. The upper part of the reactor was closed with the pyrex glass cover providing the entrance of the inert gas to the system. The lower part of the reactor was connected to the cooling system. The liquid product collection apparatus used as the cooling system was placed in the ice bath to ensure the collection of the condensable torrefaction steam. Heating of the chamber was made by using a voltage transformer. Temperature control of system was performed with a NiCr thermocouple located so as to touch upper outside surface of the reactor tube.

Before torrefaction of samples, reactor tube and liquid trap were thoroughly cleaned and dried in an oven at 105°C for 2 hours. After loading with stalks of approximately the same size and weighting the reactor and its top cup, it was placed in the chamber and connected to liquid product collection system with a piece of silicone tubing as shown in Fig. 1 Then nitrogen flow (100 ml/min.) was started to pass through the reactor and trap for 5 minutes to remove any oxygen in these spaces. Then chamber was heated to working temperature in 40 minutes and maintained at this temperature for further 10 minutes. This assured all of the apparent volatiles have evolved in this duration. After that, heating was stopped and the system was left to cool under nitrogen flow.

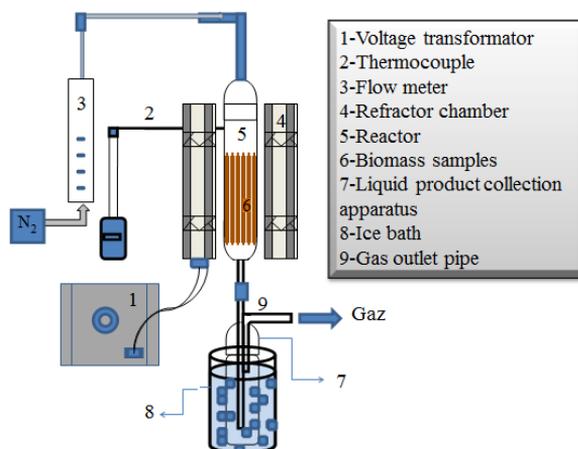


Fig.1 Torrefaction experiment system

The reactor tube with torrefied samples was removed and weighted to estimate solid yield. Liquid traps were also weighted to determine yields and inside contents were transferred into sample tubes. Then traps were rinsed with aliquots of tetrahydrofuran to clean them for the next runs. Gas product yield was estimated from difference. The

torrefaction experiments were repeated for 220 (light), 260 (medium), and 300°C (severe). The same processes were applied to prepared pellets at 260°C.

3. Results and Discussion

The colour change in the samples, depending on the temperature of torrefaction is given in Fig. 2. A coal-like view was observed to form as the temperature of torrefaction increased. The increase in weight loss with increasing process temperature is seen in Fig. 3. The high regression coefficient ($R^2 = 0.9875$) indicates a linear relationship between weight loss and the torrefaction temperature. This explains the decrease in solid product yield with increasing temperature, given in Table1. The solid yield was calculated using Eq (1).

$$\text{Solid yield (\%)} = (\text{Weight}_{\text{tor}}/\text{Weight}_{\text{raw}})\times 100 \tag{1}$$

The subscripts “tor” and “raw” represent torrefied and raw biomass, respectively.

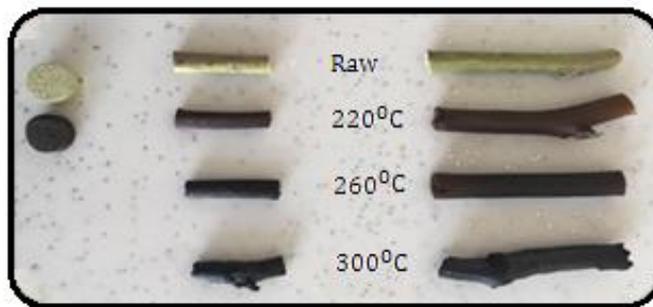


Fig. 2 View of raw and torrefied ES

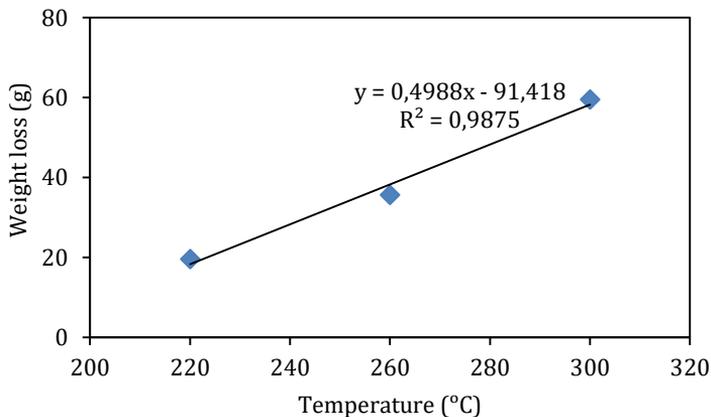


Fig. 3 Change in weight loss of ES with the torrefaction temperature

Table 1. Product yields obtained by the torrefaction of ES at different temperatures

Product	Temperature (°C)	Yield (%) (3 cm)	Yield (%) (6 cm)	Yield (%) (pellet)
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Solid	220	80.40	80.38	58.45
	260	64.34	67.02	
	300	40.48	41.50	
Liquid	220	3.35	3.50	13.74
	260	9.82	7.87	
	300	35.81	36.21	
Gas	220	16.26	16.13	27.81
	260	25.84	25.11	
	300	23.71	22.30	

Table 1 shows the product yields obtained at three different temperatures for samples of 3 and 6 cm length, respectively. Besides, the torrefaction product yields of the pellet sample at 260 °C are also given in the same table. It was determined that the amount of liquid and gas products increased as the amount of solid products decreased with rising process temperature. When biomass is heated in an inert environment, the moisture first separates and then begins to decompose. These components, which form the volatile substance, are separated by the effect of increasing torrefaction temperature and form liquid and gas products. The rising process temperature increases the degradation rate of biomass and causes the amount of solid product to decrease and amounts of liquid and gas products to increase. Therefore, it can be said that the solid yield is indicative of the severity of torrefaction. Because, when the torrefaction severity increases, the yield of solid products decreases [18]. On the other hand, it was observed that the stalk length was not effective on the product yields in the reaction zone within the reactor. When the yield of the pelletized sample was compared with that of the stalk samples at the same temperature, it was seen that less solid product and more liquid and gas product were obtained.

The proximate and ultimate analyses result of raw ES and those of the solid product obtained as a result of torrefaction process are given in Table 2. As expected it was determined that volatile matter ratio decreased and ash and fixed carbon contents increased with increased torrefaction temperature. The proximate analysis data are also confirmed by elemental analysis data.

Both the product yields and the proximate analysis results show that the pellets prepared from ES behave differently during the torrefaction process. This may be due to the structure of the pellet and the severity of the torrefaction. The structure of the pellet is affected by the moisture content, particle size and lignocellulosic structure of the biomass used [19-22]. Because the pellets were prepared from grains in the dimension of <100 mesh and had a very tight structure. In addition, the most important problem in the development of the torrefaction technology is the predictability and consistency of product quality [23]. It can be said that the temperature and the duration of the torrefaction are not sufficient for the pellet sample.

The elemental analysis results show that carbon content increased as well as oxygen and hydrogen content decreased, with increasing torrefaction temperature. This is because water and low molecular weight components were released from the biomass by devolatilization, with increasing torrefaction temperature. The reduction in hydrogen and oxygen content increases the carbon content [24,25], which leads to improvement in the fuel properties of the solid product. Atomic O/C and H/C ratios in the raw biomass are generally within the interval of respectively 0.4-0.8 and 1.2-2.0. While hydrogen and oxygen from the torrefied biomass are separated by moisture and light volatiles, carbon is retained. This situation causes the carbonization of the biomass. The Van Krevelen diagram in which the atomic H/C ratio is plotted against the atomic O/C ratio is shown in

Fig. 4. Linear distribution between the two ratios are obviously exhibited in that the regression coefficient of determination ($R^2= 0.9669$) is high. The two ratios decrease with increasing torrefaction severity [23,26,27]. The slope of the regression line is 1.62, indicating that the impact of torrefaction on the atomic H/C ratio is larger than on the atomic O/C one by a factor of approximately 1.6. The atomic O/C and H/C ratios of the raw sample were found to be 0.98 and 1.91, respectively. In the Van Krevelen diagram, it was determined that ES has approached to the area of cellulose. In this case, it can be said that the ES has high cellulose ratio. It has been observed that O/C and H/C ratios of torrefied ES have been into the interval of 0.4-0.7 and 1.0-1.6 respectively. It was determined that the ratio of lignin in the sample increased with increasing process temperature. The clear change in the ratios of H/C and O/C as a result of the torrefaction process conducted at 300°C in the nitrogen atmosphere is caused by the disintegration of cellulose in this temperature zone [16]. In the Van Krevelen diagram, it has been detected that torrefied samples have approached to the area where peat and lignin were present.

Table 2. The Proximate and ultimate analysis of raw and torrefied samples (* determined from difference)

	Raw	Torrefied			
		220°C	260°C	300°C	Pellet (260°C)
Proximate analysis (%)					
Volatile matter	77.00	72.00	60.10	41.70	58.20
Ash	6.10	4.20	6.10	9.70	12.40
Fixed carbon *	16.90	23.80	33.80	48.60	29.40
Ultimate analysis (%)					
C	40.20	47.50	53.80	62.40	
H	6.40	6.54	5.62	5.06	
N	0.40	0.50	0.30	0.70	
S	0.11	0.04	-	0.08	
O*	52.89	45.42	40.28	31.76	

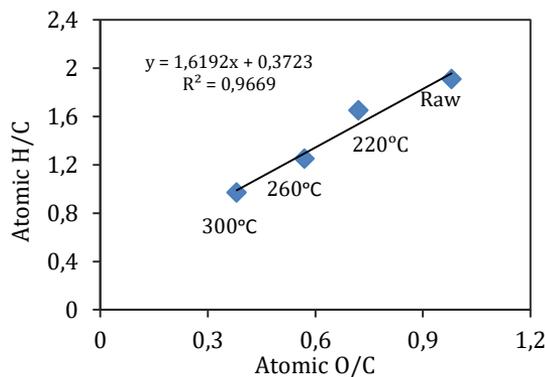


Fig. 4 Change of the atomic H/C and O/C ratios of the raw and torrefied WVS (Van Krevelen diagram)

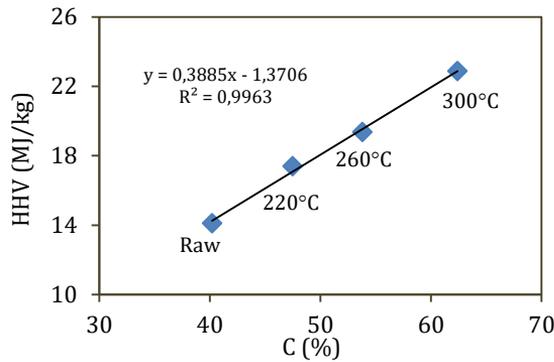


Fig. 5 Change of carbon ratio and HHV of raw and torrefied ES

Fig. 5 shows that HHV increases with the increasing carbon ratio. It is seen that there is a strong linear relationship between HHV and carbon ratio ($R^2=0.9963$). The hydrogen and oxygen content decreasing together with the increasing carbon in the biomass causes the HHV to increase. The carbon contained by the fuel is the main resource of the heat occurring during the combustion. Hydrogen is also one of the main resources of the combustion heat. However, the excessive hydrogen in the fuel reduces the carbon ratio. The oxygen in the biomass helps the combustion of the fuel, but decreases the heat value of the biomass [16, 28]. This result clearly indicates that the HHV of torrefied biomass can be predicted from the carbon ratio.

Table 3. The effect of process temperature on HHV and energy yield

Sample	Solid Yield (%)	HHV (MJ/kg)	Enhancement factor of HHV	Energy Yield (%)
Raw		14.10		
220°C	80.40	17.46	1.24	99.70
260°C	64.34	19.37	1.37	88.15
300°C	40.48	22.87	1.62	65.58
Pellet (260°C)	58.45	17.14	1.22	71.31

Table 3 shows the effect of the process temperature on HHV and energy yield. It was detected that with the increasing temperature, the HHV increased and the energy yield decreased. While the carbon content of the biomass increases as the torrefaction temperature rises, oxygen content decreases [5]. This situation causes to the increase in HHV as the torrefaction temperature increases. It was determined that the HHV increased by 62% when the carbon amount increased by 55% in the torrefaction conducted at 300°C. It was also observed that the energy yield has decreased to 65.58% with the increasing torrefaction temperature. Energy yield can be considered as an important indicator of the amount of energy retained after torrefaction [29]. The energy yield, determined on the basis of solid product yield and HHV, is an indicator of the amount of energy preserved during torrefaction [3]. The energy yield was calculated using Equation 2 and 3 [30]. Taking into account Equation 3, the energy yield is largely dependent on the mass yield values, and it can also be concluded that the energy yield depends on the biomass type [31-33].

$$\text{Enhancement factor of HHV} = \text{HHV}_{\text{tor}} / \text{HHV}_{\text{raw}} \tag{2}$$

$$\text{Energy yield \%} = \text{solid yield \%} \times \text{Enhancement factor of HHV} \tag{3}$$

Here; HHV_{tor} and HHV_{raw} respectively show the higher heat values of the torrefied and raw biomass.

The HHV of coal often ranges between 25-35 MJ/kg. It is stated in the literature that the heating value of biomass approximates that of coal as the temperature of torrefaction process increases [12]. It was determined that 65.6% of the energy of the torrefied ES (300°C) was maintained and its HHV approximated that of coal. In the light of these information, this temperature can be said to be appropriate for ES torrefaction process to be performed.

4. Conclusion

The results obtained from this study, in which agriculture waste is aimed to be converted to a usable solid fuel by torrefaction process, are given below:

It was determined that the weight loss of the sample increased and the solid product yield decreased with the increased treatment temperature. In this case, it can be said that the yield of solid products is indicative of the torrefaction severity.

It was observed that the stalk length was not effective on the product yields. Also the high mass loss at 300°C indicated that the eggplant stalks have a high cellulose ratio.

It was concluded that the pellets treated at 260°C behaved differently from the raw sample and the torrefaction severity was not sufficient for the pellets.

It was determined that the ratio C of the solid product increased with the torrefaction severity, the H and O ratios decreased. As a result, O/C and H/C ratios decreased. The net change in H/C and O/C ratios of torrefied ES was detected in 300°C and fuel properties of biomass approached coal.

The energy efficiency decreased and HHV increased with increasing torrefaction severity. It was found that 65.58% of the energy of the biomass was maintained under severe torrefaction conditions. The energy yield is largely dependent on the mass yield values and it can also be said that the energy yield depends on the biomass type. Also it was determined that the HHV increased by 62% when the carbon amount increased by 55% in the torrefaction process conducted at 300°C.

It was found that as in many agricultural wastes left to decay at the end of the production season, the fuel properties of eggplant stalks, left to decay, can be improved through torrefaction process. It was determined that the fuel properties of solid product obtained in severe torrefaction conditions (300°C) approximated those of peat. Consequently, it can be said that the solid product obtained from agriculture waste after severe torrefaction conditions can be burned alone or together with coal.

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