Sugarcane Bagasse Pyrolysis: Investigating the Effect of Process Parameters on the Product Yields.

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Abstract

The objective of the present work is to investigate the pyrolysis of sugarcane bagasse in a semi-batch reactor and study the effect of process parameters of pyrolysis on the products yield to determine optimum parameters for maximum bio-oil production. Parameters of the pyrolysis process such as temperature, particle size of sugarcane bagasse and flow rate of nitrogen (N_2) have been varied as 350–600 ºC, 0.25–2 mm and 100–500 cm^3/min, respectively. According to the various pyrolysis conditions applied in the experimental studies, the obtained oil, char and gas yields ranged between 38 and 45 wt%, 24 and 36 wt%, and 23 and 37 wt%, respectively. The maximum pyrolysis bio-oil yield of 45 wt% was achieved at temperature of 500 ºC, particle size of 0.5 -1 mm with nitrogen(N_2) flow rate of 200 cm^3/min. Based on the results captured under this study's pyrolysis conditions, temperature is considered to be the most important parameter for product distribution. As the increases of the pyrolysis temperature the bio-char yield decreased and increase of gas yield. The bio-oil yield increases with increasing the temperature, reaches a maximum value at about 500 ºC and reduces thereafter at higher temperature is expected due to secondary cracking reactions of the volatiles, which results produce a higher gaseous yield.

1. Introduction

In Egypt, the fossil fuel (e.g., oil, coal, natural gas) is a primary source of energy which can cause health problems and environmental damage. Moreover, the recent increasing the price of conventional fossil fuel, global warming, climate change are the primary reasons to find alternative, cheaper, reliable and renewable resource to fulfill energy demand and substitute fossil fuels when the reserves are exhausted. In parallel, the agricultural wastes cause different problems to rural areas in Egypt, which causes soil and air pollution problems. The highest quantities of wastes are producing from some crops such as sugarcane, rice, corn, wheat and cotton. These waste materials include bagasse (sugar cane bagasse), straw (rice straw), cobs (corn cobs), and peel (banana and orange peel). The quantity of agricultural waste in Egypt is between 22 and 26 million dry tons per year [1]. So that, the large quantity of wastes should not be burned or disposed but should be rather treated as raw material for other industries. Sugarcane is the one of the largest agricultural crops in Egypt and bagasse is a major byproduct of the sugar industry, over 16.2 million tons of sugarcane is produced from over 125000 hectares of land, with an average yield of 126 tons/hectare[2]. Generally, one ton of sugarcane produces around 112 kg of sugar, 310 kg of dry bagasse and 41 kg of molasses[2]. Bagasse is a lignocellulosic residue remained after collecting the valuable parts of crops, which consists of around 40–50% cellulose, 20–30% hemicellulose, 20 – 25% lignin and 1.53% ash [3].

Bagasse is used for different purposes in different sugar mills. It is used for steam and power generation in Nagaa Hammadi Sugar Mill in the manufacture of fiberboard in Deshna Sugar Mill and in pulp and paper manufacture in Kous Sugar. The bagasse used to produce steam and electricity as a source of fuel for boilers. The bagasse's burning efficiency is only 60%, and bagasse is usually supplemented by another fuel such as fuel oil to increase the efficiency of combustion, which produce emissions due to high sulfur in fuel oil. So that bagasse cane is be used as renewable source of energy for production biofuels through thermochemical conversion processes [4].

Pyrolysis is a thermochemical conversion process used to convert biomass and organic materials into biofuels namely bio-oil, biochar and non-condensable. It is defined as the thermal decomposition of biomass in a closed reactor in absence of oxygen. The pyrolysis products distribution depends on process parameters as well as the compositions of biomass. The most important parameters are the type of reactor, pyrolysis temperature, heating rate, biomass particle size, residence time and sweeping gas flow rate (N_2)[5]. The product yield of the pyrolysis depends on the operating parameters, properties of biomass, type of the pyrolysis process. Controlling and optimizing these parameters is a very important in order to maximize bio-oil yields and optimal product distribution.

Pyrolysis of different types of biomass such as olive bagasse [6], hazelnut bagasse [7], grape bagasse [8], orange bagasse [9] and sugarcane bagasse [10–13] has been performed in different types of reactors such as batch, semi-batch and continuous reactor. In most of these literatures, the effects of different operating parameters on products yield have been investigated. A. K. Varma and P. Mondal.[11] investigated the influence of pyrolysis temperature, heating rate, particle size range and sweeping gas flow rate on product yields from sugarcane bagasse pyrolysis in a semi batch fixed-bed reactor. The temperature of pyrolysis and heating rate were varied in the range 350–650 ^oC and 10–50 $^oC/min$ respectively. The particle size was varied in the range < 0.25– 1.7 mm and nitrogen flow rate 50–200 cm^3/min. The result shows that the maximum bio-oil yield was 45.23% was obtained at 500 ^oC, heating rate of 50 $^oC/min$, particle size of 0.5–0.6 mm and nitrogen flow rate of 100 cm^3/min.

In this research, sugarcane bagasse pyrolysis was performed in a semi-batch reactor. The effects of pyrolysis temperature, particle size range and nitrogen flow rate on the pyrolysis product yields are explored to determine the optimal pyrolysis parameters for maximum bio-oil production.

2. Material And Methods

2.1 Feedstock

A sugarcane bagasse sample investigated in this work was obtained from Nagaa Hammadi sugar factory. The sample was sieved to the size range of $0.25 < Dp < 0.5$, $0.5 < Dp < 1$, $1 < Dp < 2$ and $Dp > 2$ mm with the help of standard sieve (Zhejiang Tugong instrument Co). Before the experiments, the sample was dried in an oven at 105 ºC for two hours to remove the excess moisture and then stored in air tight plastic bags. Table 1 shows the main characteristics of the raw material sample. Figure 1 (a, b, c and d) shows sugarcane bagasse sample and sugarcane bagasse bio-char, bio-oil and bio-gas.

Table 1
Main characteristics of the sugarcane bagasse

Characteristics	Results	Methods [24]
Proximate analysis (wt%)		
Moisture content	4.9	ASTM D-7582
Volatile matter	82.47	ASTM D-7582
Ash content	2.85	ASTM D-7582
Fixed carbon	9.78	ASTM D-7582
Ultimate analysis (wt%)		
Carbon (C)	46.87	ASTM D-5373
Hydrogen (H)	6.94	ASTM D-5373
Nitrogen (N)	0.34	ASTM D-5373
Sulfur (S)	0.13	ASTM D-4294
Oxygen (O)	45.72	By difference
O/C molar ratio	0.73	Calculation
H/C molar ratio	1.78	Calculation
Empirical formula	$CH_{1.78} O_{0.73} N_{0.006}$	Calculation
HHV (MJ/kg)	18.45	ASTM D-240

2.2 Experimental Setup

The pyrolysis tests of sugarcane bagasse were performed in a laboratory scale cylindrical semi-batch pyrolysis reactor as shown in Fig. 2 [14]. The reactor was made of 304 stainless steel with a diameter of 10 cm and a height of 40 cm. The reactor was externally heated by electrical furnace with 2.5 kW power thermal insulation was used to reduce the heat loss. The temperature of pyrolysis was measured by using a K-type thermocouple. Temperature inside the reactor was maintained constant by using a PID controller was used to control the temperature inside the reactor. The nitrogen gas (N_2) was used to create an inert condition within the reactor and to transport the pyrolysis vapors to the condensers. The condensation system consists of three condensers (one stainless steel and two glass condensers) and the condensed liquid was collected in a flask and weighted for yield. After each run, the char was removed from the reactor by using of the screw system and collected and weighed. The non-condensable gas was calculated by difference between total biomass feed and sum of liquid and char yield. The product yields were calculated according to the following equations [15]:

$$\text{Bio-oil yield (\%)} = \frac{\text{Bio-oil yield}}{\text{Feeding weight}}\ x\ 100 \quad (1)$$

$$\text{Bio-char yield (\%)} = \frac{\text{Bio-char yield}}{\text{Feeding weight}}\ x\ 100 \quad (2)$$

$$\text{Bio-gas yield (\%)} = 100 - (\text{bio-oil yield} + \text{bio-char yield}) \quad (3)$$

2.3 Experimental Procedure

The experimental procedures of sugarcane bagasse were performed in three groups to study the effect of pyrolysis parameters on products yields and to determine the optimum parameters for maximum bio-oil production. For every run about 100 g of the feedstock sample was placed inside the biomass feeding hopper. When the reactor reaches to the set temperature, the sample dropped down into the reactor by the action of screw feeder. Before each run, the reactor purged with N_2 gas flow rate of 200 cm^3/min to provide an inert atmosphere inside the reactor.

The first experimental group was conducted to determine the effect of temperature on the pyrolysis yields of sugarcane bagasse. Dried sugarcane bagasse sample with particle size (Dp) of $0.5 < Dp < 0.1$ mm was dropped into reactor after the reactor reached to the final pyrolysis temperature. The reactor was heated to final pyrolysis temperature of 350, 400, 450, 500, 550, and 600 ºC at N_2 flow rate of 200 cm^3/min. for every run, the experiment was adjusted at the set temperature and continued until no notable release of brownish vapor was observed at the reactor outlet.

The second group of experiments were conducted to investigate the effect of different particle size ranges of $0.25 < Dp < 0.5$, $0.5 < Dp < 1$, $1 < Dp < 2$ and $Dp > 2$ mm on the pyrolysis product yields. For all experiments the final pyrolysis temperature and N_2 flow rate were 500 ºC and 200 cm^3/min, respectively, based on the results from the first group of experiments.

The third experiment group was conducted to determine the effect of sweeping gas (N_2) flow rate on product yields. The experiments were conducted with N_2 flow rates of 100, 200, 300, 400 and 500 cm^3/min at constant final pyrolysis temperature of 500 ºC and particle size of $0.5 < Dp < 0.1$ mm, respectively, based on the results of the first and second experimental groups.

3. Results And Discussion

3.1 Effect of Operating Parameters on the Product Yields

Figure 3 shows the effect of pyrolysis temperatures between 350–600 ºC with step 50 ºC on the products yield distribution from the pyrolysis of sugarcane bagasse with particle size of $0.5 < Dp < 1$ mm with nitrogen flow rate of 200 cm^3/min. It is observed that from Fig. 3 as the temperature increases from 350 to 600 ºC the char yield decreases from 36 wt% to 26 wt% while the gas yield increased from 26 wt% to 29 wt%. As the pyrolysis temperature increases the bio-char yield decreased and gas yield increased due to the secondary decomposition and volatilization of char at higher temperature [16, 17]. As the pyrolysis temperature increases from 350 to 500 ºC the bio-oil yield raises from 38 wt% to 45 wt% and then decreases to 39 wt% as the temperature increases to 600 ºC. The decrease in the production of bio-oil at higher temperatures is due to secondary cracking reactions of pyrolysis vapors, which results produce a higher gaseous yield as well as secondary decomposition of char, which increases non-condensable gaseous products, therefore liquid yield decreases[17, 18]. From the above discussion, it is concluded that the gas yield products and char yield decrease with temperature and the process temperature has a significantly effect on the distribution of the products yield. For present study, the maximum bio-oil yield of 46 wt% was achieved at pyrolysis temperature of 500 ºC. Similar results from pyrolysis of sugarcane bagasse have been obtained, where the maximum bio-oil yield of 45.23 wt% was obtained at temperature of 500 ºC [11].

Figure 4 shows the effect of sugarcane bagasse particle size on the product yields distribution at constant pyrolysis temperature of 500 ºC and sweeping gas (N_2) flow rate of 200 cm^3/min. From Fig. 4 it is observed that the bio-char yield increases and gas yield reduces with increasing the biomass particle size. As the particle size of sugarcane bagasse increases from $Dp < 0.5$ mm to the range of $Dp > 2$ mm bio-char yield increases from 27 wt% to 36 wt% and the yield of bio-gas products decreases from 35 wt% to 23 wt%. This occurs because of larger particles size greater gradients exist inside it so that the core temperature is lower than the surface temperature, which possibly gives increase in the char yield and decrease in the bio-oil and gaseous yields [6]. The smaller particle size of $Dp < 0.5$ mm the bio-oil yield is produced as 38 wt% and for larger particle size of $Dp > 2$ mm, bio-oil yield is produced as 41 wt%. Only 3% difference in bio-oil yield obtained for smaller and larger size of particle. According to the considered important on the product yields distribution. Generally, for pyrolysis is preferred smaller particle size due to their uniform heating and produces higher amount volatile matter and increases gaseous products and the bio-oil yield. In contrast, for larger particle size high-temperature gradient inside the particle resulting less heat transfer from outer to inner surface of the particle and possibly decreases the bio-oil and bio-gas yield and increases the bio-char yield [19]. Similar effect of the particle size was also observed in the literature, where the large particle size causes increasing in the bio-char and decreasing in the bio-oil [11, 20].

Figure 5 shows the effect of N_2 gas flow rate on the products yield at constant pyrolysis temperature of 500 °C and biomass particle size of $0.5 < Dp < 1$ mm. Flow rate of nitrogen is important in the pyrolysis process. It creates an inert condition inside the pyrolysis reactor and also reduces the vapor residence time and reduce the secondary reactions and the probability of thermal cracking and repolymerization of vapors to maximize the bio-oil yield [21]. Therefore, it is necessary to quickly quench, cool and remove the pyrolysis vapors from the reaction zone to minimize secondary reactions [22]. The bio-oil product yield increases from 39 wt% to 45 wt%, when N_2 flow rate increases from 100 to 200 cm^3/min, however, when the flow rate of the nitrogen gas increases up to500 cm^3/min the yield of bio-oil decreases to 39 wt%. This is because of the higher flow rate of N_2 the pyrolysis vapors which are produced from reactor with nitrogen flow without sufficient condensation[23]. As N_2 flow rate increases from 100 to 500 cm^3/min the bio-char yield decreases from 36 wt% to 24 wt% and product bio-gas yield increases from 25 wt% to 37 wt%. The maximum bio-oil product yield of 46 wt% is found at N_2 flow rate of 200 cm^3/min. It is observed that the particle size of biomass, optimum pyrolysis temperature and N_2 gas flow rate mainly vary as $0.5 < Dp < 1$ mm, 500–550 °C and 100–200 cm^3/min respectively. The bio-oil yield change in the range of 34–66 wt%. The variation in the oil yield may be due to the variation in operating parameters as well as the biomass properties Table 2.

Table 2
Comparative study of sugarcane bagass pyrolysis with other different types of biomass.

Type of Biomass	Reactor Type	Temperature (ºC)	Particle size (mm)	N_2 flow rate (cm^3/min)	Bio-oil yield (wt%)	References
Sugarcane bagasse	Semi-batch	500	0.5–1	200	45	Present study
Sugarcane bagasse	Semi-batch	500	0.5–0.6	100	45.23	[11]
Sugarcane bagasse	Semi-batch	500	0.5-1	200	66.1	[12]
Sugarcane bagasse	Batch	560	0.5–0.85	116	53.83	[25]
Orange bagasse	Semi-batch	525	0.425	200	35.53	[9]
Olive bagasse	Semi-batch	500	0.45–0.6	150	34.4	[6]
Grape bagasse	Fixed bed	550	-	100	41.6	[8]

4. Conclusions

In a semi-batch reactor, sugarcane bagasse pyrolysis runs were performed to study the influence of final pyrolysis temperature, particle size of biomass and flow rate of N_2 on product yield. The experimental results showed that the highest bio-oil yield of 45 wt % was achieved at temperature of 500 ºC, particle size of $0.5 < Dp < 1$ mm with 200 cm^3/min nitrogen gas flow rate. As the pyrolysis temperature rises, the yield of the bio-char decreased and the yield of gas increased. The yield of bio-oil increases with higher temperatures, reaches a maximum value of around 500 ºC and then decreases at higher temperatures due to secondary cracking reactions of the volatiles, which results produce a higher gaseous yield. As the particle size increased no significant effect on the yield of bio-oil where the difference in the yield of bio-oil for smaller and larger particle size is only 3%. The bio-char yield increases while the bio-gas yield is decreased. The yield of bio-oil has been increased as the flow rate of nitrogen increases from 100 to

200 cm^3/min, then decreases as the sweep gas flow rate increases up to 500 cm^3/min the yield of bio-oil decreases. This is because the volatile components are drawn out of the reactor with nitrogen stream without proper condensation due to a higher flow rate of N_2, thus increasing the bio-gas yield and lowering the bio-char yield. It is observed that the particle size of biomass, optimum pyrolysis temperature and N_2 gas flow rate mainly vary as$0.5 < Dp < 1$ mm, 500–550 °C and 100–200 cm^3/min respectively.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

All the data generated and analyzed during the study are included in the main manuscript.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

This research concept, design, and development were by MRO and AGH, as well as supervised by SSW. The manuscript was written and edited by AGH, MRO and SSW. All authors read and approved the final manuscript.

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Figures

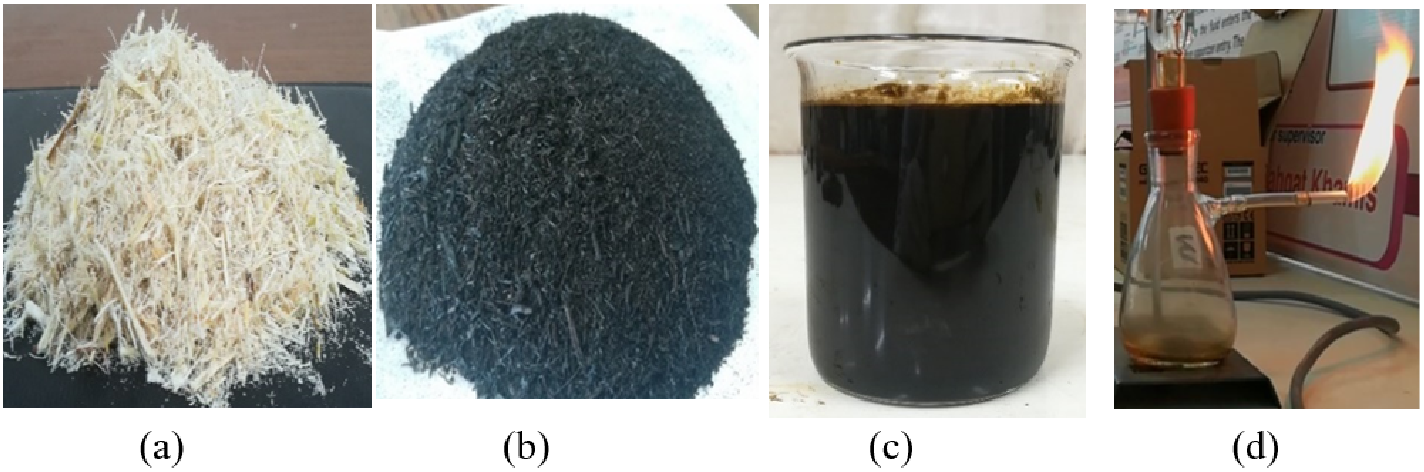

Figure 1

a) sugarcane bagasse, b) bio-char, c) bio-oil and d) flared gas

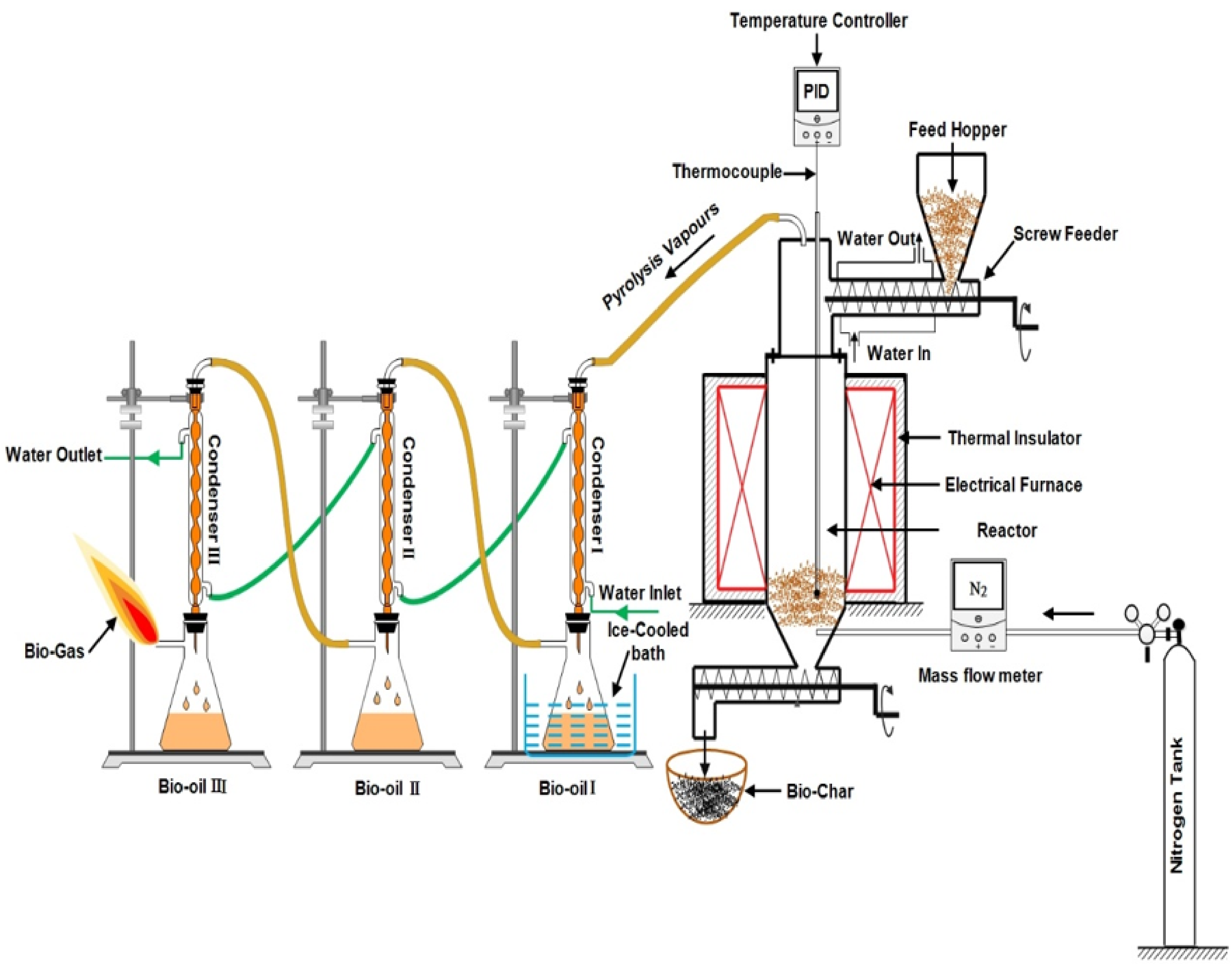

Figure 2

Schematic diagram of the experimental set-up.

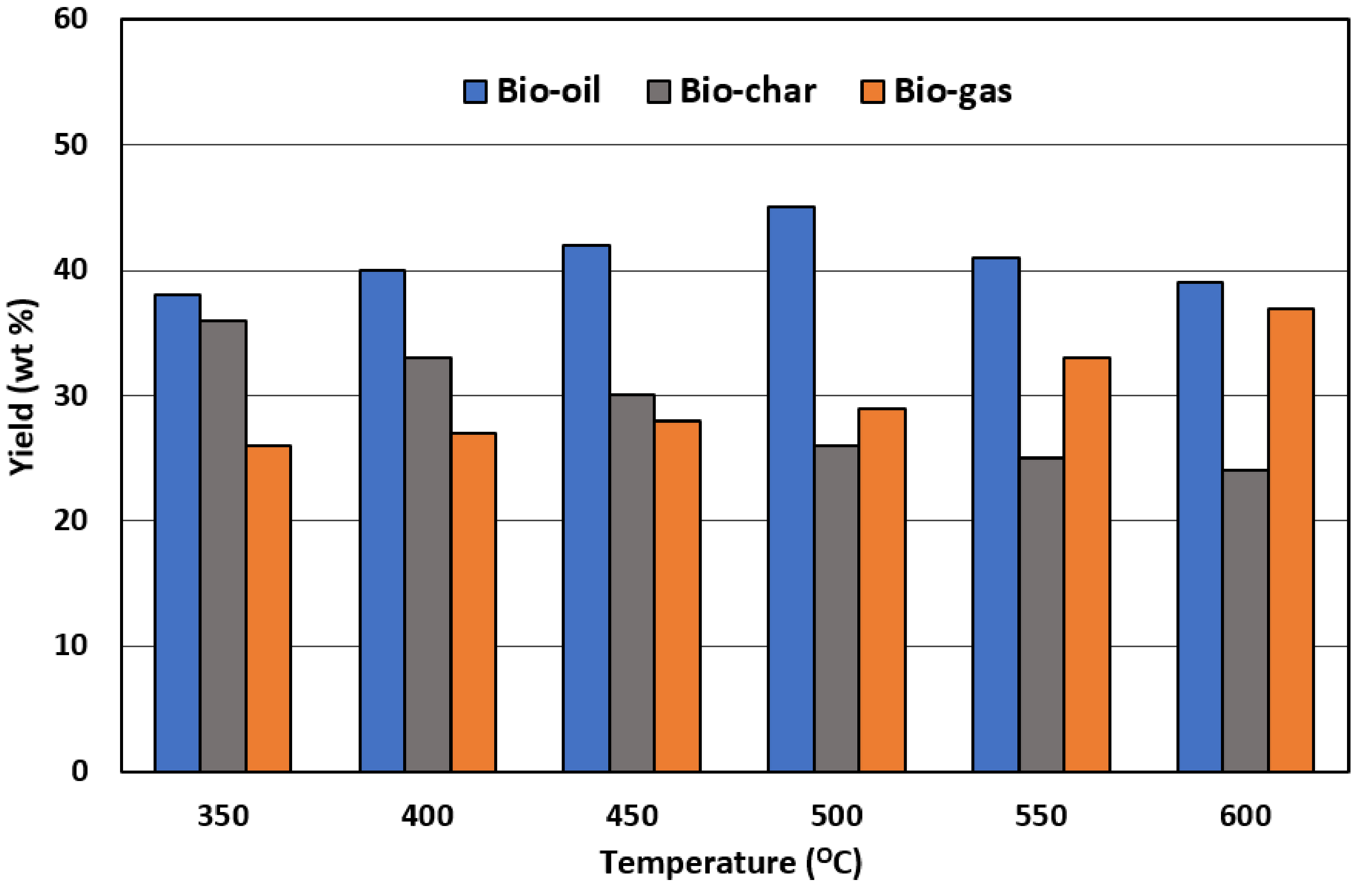

Figure 3

Effect of pyrolysis temperature on product yields at particle size of 0.5<Dp<1 mm and (N2) flow rate of 200 cm3/min.

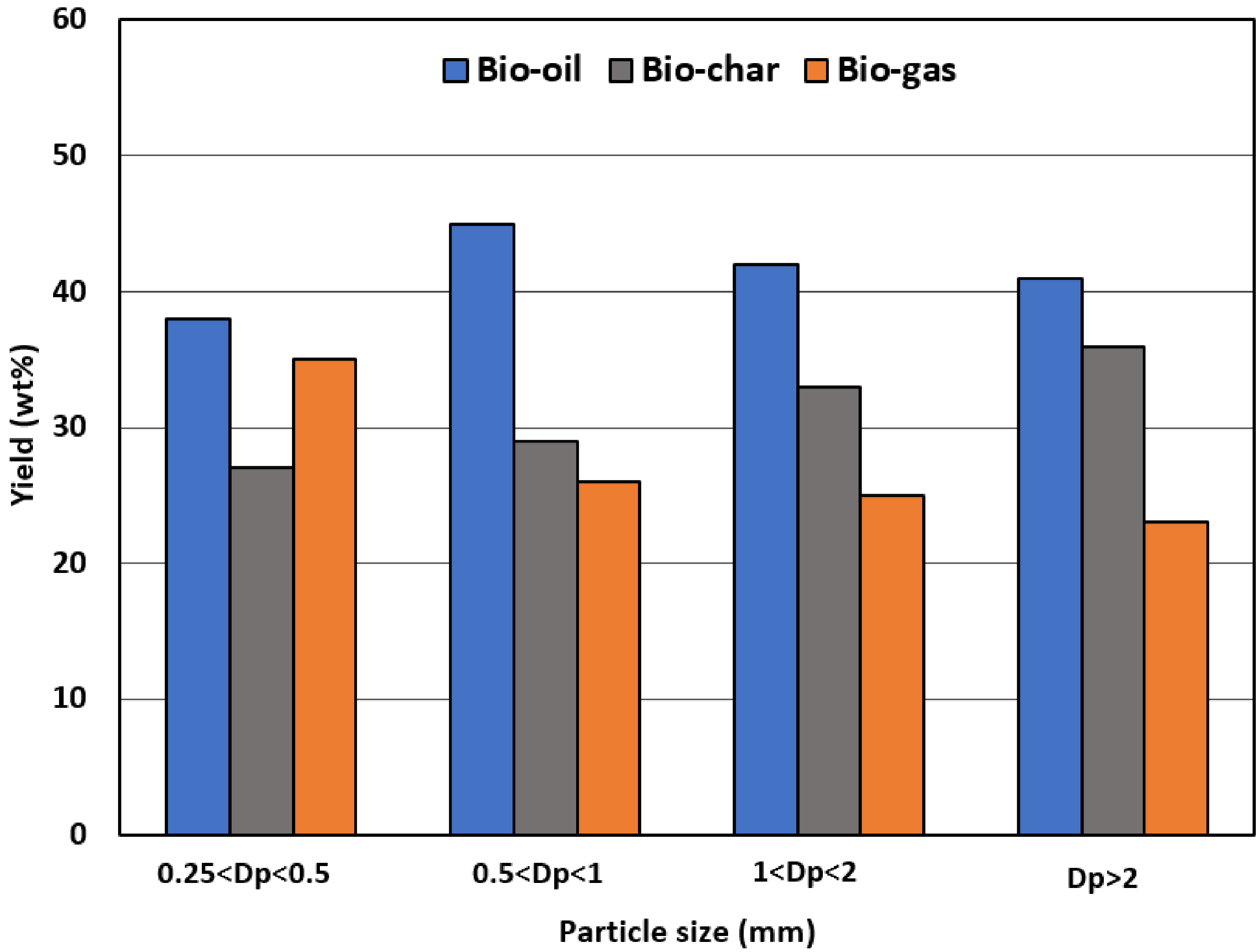

Figure 4

Effect of particle size on the product yields at temperature of 500 ºC and (N2) flow rate of 200 cm3/min.

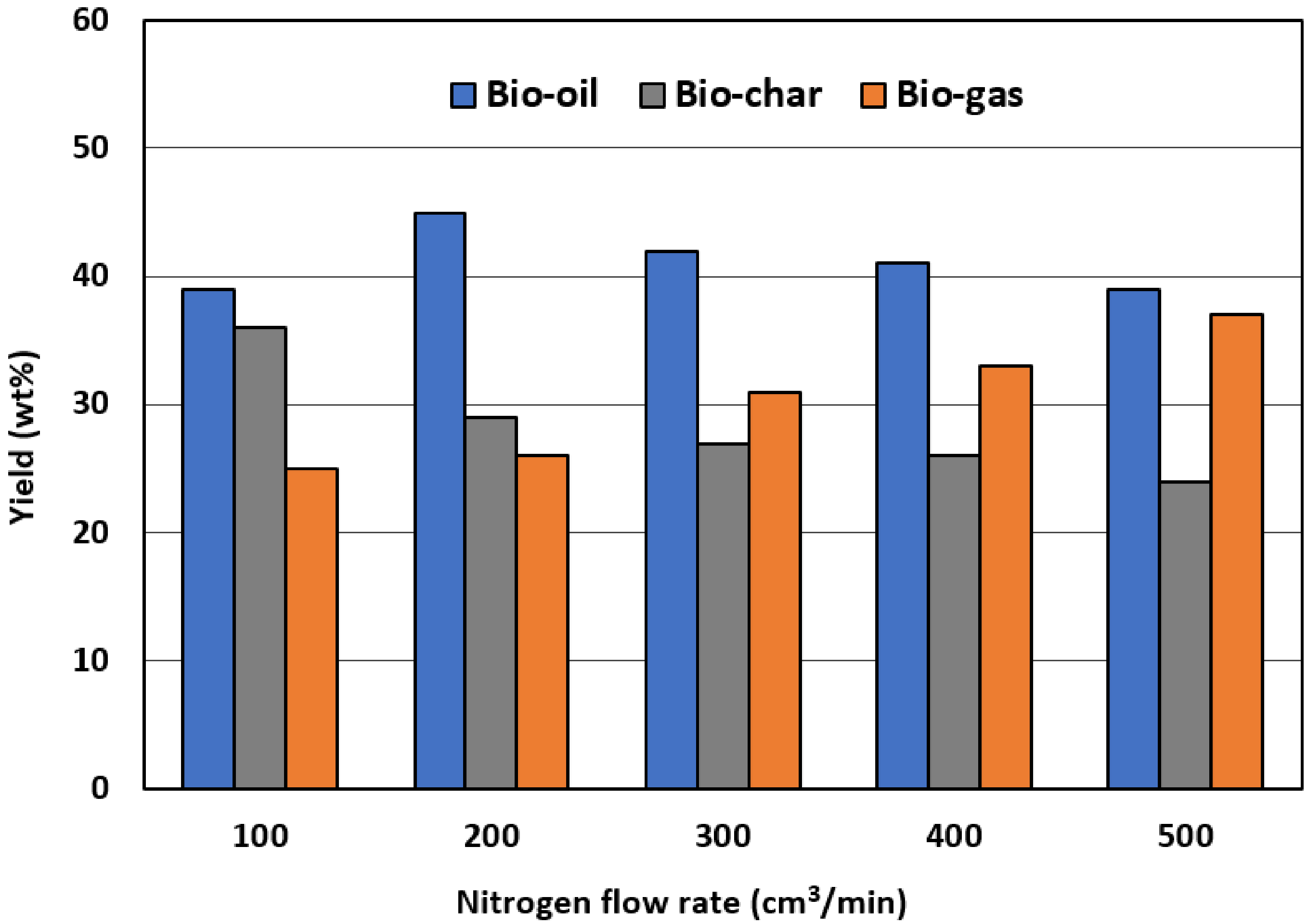

Figure 5

Effect of nitrogen flow rate on product yields at pyrolysis temperature of 500 ºC and particle size of 0.5<Dp<1 mm.

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