Investigation of the effects of outlet air flow rate and chamber temperature on some properties of wheat straw biochar in a fixed-bed oxidative pyrolysis

Milad Eghbali[1], Esmaeil Mirzaee- Ghaleh[1*], Ali Nejat Lorestani[1], Hekmat Rabbani[1], Mahmud Khoramivafa[2]

(1. Mechanical Engineering of Biosystems Department, Razi University, Kermanshah, Iran;
2. Production Engineering and Plant Genetics Department, Razi University, Kermanshah, Iran, 6714414971)

Abstract: Soil plays an important role in the sustainability of ecosystems. In recent years, the increasing growth in the degradation of soil resources has drawn attention to management strategies for maintaining the soil quality. Researchers have recently studied the impact of using biochar on physical and chemical properties of soil. It has been found that adding biochar improves the soil quality. Some factors such as pyrolysis chamber conditions, pyrolysis peak temperature and air flow rate affect the physical and chemical properties of biochar including the density, pH, ash content, and so on. In this study, the effect of changes in the air flow rate and chamber temperature in the fixed-bed oxidative pyrolysis on the biochar yield, ash content, density and pH were investigated. For this purpose, a fixed-bed biochar production apparatus with varying chamber temperature and flow rate of outlet air was designed and manufactured. The experiments were performed at four air flow rates of 20, 25, 30 and 35 $L min^{-1}$ and four temperatures of 350°C, 400°C, 450°C and 500°C for wheat straw. The results showed that increasing the temperature and flow rate of the outlet air from the chamber increased the ash content and pH. However, increasing these parameters decreased the biochar bulk density and yield.

Keywords: air flow rate, biochar, oxidative pyrolysis, temperature.

Citation: Eghbali, M., E. Mirzaee-Ghaleh, A. N. Lorestani, H. Rabbani, and M. Khoramivafa. 2021. Investigation of the effects of outlet air flow rate and chamber temperature on some properties of wheat straw biochar in a fixed-bed oxidative pyrolysis. Agricultural Engineering International: CIGR Journal, 23(3): 165-172.

1 Introduction

Soil plays an important role in the sustainability of ecosystems. Therefore, using the soil without proper knowledge can seriously disrupt the ongoing processes in the soil. On the other hand, producing one centimeter of soil requires more than several generations. In recent years, the increasing growth in the degradation of soil resources has drawn attention to the management strategies for using of natural resources to hold the balance between the production and improvement in the quality of natural resources (Sobhaniyan Nezhad, 2011). One of the current problems of societies is the improper use of waste from agricultural biomasses and incineration of waste in urban living environments, which causes the environmental pollution, bacterial spread, diseases, and acid rain.

The biomass existing in rural areas is a clean and renewable source of energy (Zhang et al., 2012). Pyrolysis is a thermochemical conversion process that results in the production of light gases, active materials

Received date: 2020-02-27 **Accepted date:** 2020-11-15

***Corresponding author: Esmaeil Mirzaee- Ghaleh,** Ph.D, Mechanical Engineering of Biosystems Department, Razi University, Kermanshah, Iran. Tel: +988338324820. Fax: +988338324820. Email: e.mirzaee@razi.ac.ir.

and biochar with the thermal degradation of biomass in the environments without oxygen or with low oxygen. In the past, charcoal was used as a sustainable material to absorb pollutants and improve the soil quality. The use of biochar in soil will increase soil fertility by providing a suitable habitat for the microorganisms (Javdani Soodi et al., 2012). The production of biochar from agricultural waste reduced the environmental pollution (Wu et al., 2013). It has also been demonstrated that biochar could absorb some pollutants within the soil and thereby reducing the water and soil pollution (Ahmad et al., 2014).

Biochar application in soil has been suggested as a method to prevent climate change through the long-term carbon sequestration in soil (Wolf et al., 2010) because pyrolysis may produce a biochar highly resistant to degradation (Amonette and Joseph, 2009). The pyrolysis process (in terms of heating rate) is divided into slow pyrolysis and fast pyrolysis. If the time required for performing the pyrolysis process is less than the time required to reach the pyrolysis temperature, this process is called the slow pyrolysis; otherwise, it is the fast pyrolysis (Basu, 2010).

The yield of each major product from pyrolysis depends on the pyrolysis conditions. (Di Blasi, 2008). The wide range of pyrolysis processes results in the formation of biochars that are very different in terms of elemental and ash composition, density, porosity, pore size distribution, specific surface area, surface chemical properties, absorption and desorption of water and ions, pH, and uniformity of physical structure (Laird et al., 2010).

In a study, sludge generated from wastewater treatment plant of pulp and paper industry was utilized as feedstock for the preparation of biochar using pyrolysis. The effect of pyrolyser temperature and sludge retention time on biochar yield was studied and the results were quantified in terms of % biochar yield. To study the influence of temperature on biochar yield, temperature was varied from 500^{o}C to 700^{o}C (Devi and Saroha, 2013). In a research, the impact of pyrolysis temperature and the type of biomass on the physicochemical characteristics of biochar and its impact on soil fertility were reviewed (Tomczyk et al., 2020).

One solution to supply the energy required for the pyrolysis process is to burn part of the biomass by inletting a small amount of air into the pyrolysis furnace. In the oxidative atmosphere, pyrolysis begins at lower temperatures and the decomposition is faster than inert atmosphere (Daouk et al., 2015). Under the oxidative conditions, the fixed-bed pyrolysis results in the flame-free combustion and formation of a stable ignition front beneath the bed surface (Milhé et al., 2013). In the fixed-bed pyrolysis, the heat required thermal energy is supplied by an external source or by limited combustion. The cheapness, scalability and capability of industrialization are some benefits of this type of pyrolysis. The knowledge about the thermal behavior of large biomass samples is a key component for optimizing the thermal behavior of biomass (Bridgwater, 2003).

Pyrolysis is a complex process that is affected by various factors. These factors directly affect the characteristics and efficiency of products. So far, many experimental models have been performed to explain the process of conversion of biomass into pyrolysis products, but parts of it have not yet been fully understood. The physical and chemical properties of biochar are affected by various factors such as the type of raw materials, pyrolysis unit conditions, heating rate, biochar particle size, pyrolysis peak temperature, and duration of pyrolysis. Based on the literature, there is no any study about the effect of changes in the air flow rate and chamber temperature (with together) on produced biochar properties. For the optimal designing of heat treatment furnaces, it is necessary to be aware of the mechanisms that occur during the heat conversion processes. Therefore, the purpose of the present study was to investigate the effect of changes in the air flow rate and chamber temperature in the fixed-bed oxidative pyrolysis on some biochar properties of wheat straw.

2 Materials and methods

In this study, the effects of variation of chamber temperature and outlet air flow rate on the biochar characteristics of wheat straw were investigated. For this purpose, wheat straw was collected from an agricultural land and the additional materials, animal manure and inorganic residues were removed. The initially moisture content of used wheat straw was 10% w.b. The biochar production apparatus was designed and fabricated by the fixed-bed oxidation method (Figure 1).

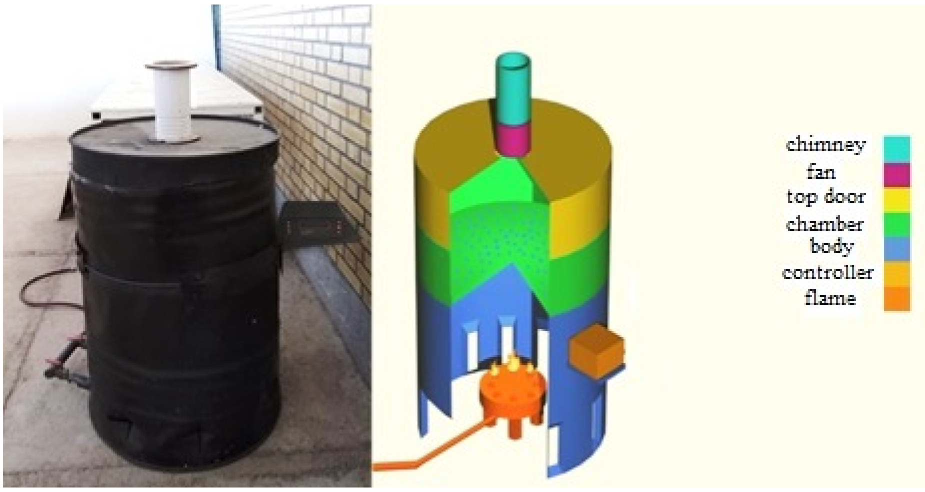

Figure 1 Schematic and real images of fabricated biochar production apparatus.

The used apparatus was consisted of a cylindrical steel body with height of 1.5 m and diameter of 1 m including two main parts: heating unit and pyrolysis unit. Beneath the pyrolysis unit was designed and fabricated with a perforated bottom to pass hot air through the bottom of the chamber and to continue moving through the biomass. To maximize the space available for biochar production, the diameter of the pyrolysis unit had the same size as the body of the apparatus. The top of the pyrolysis chamber is a steel door for charging the biomass with a circular hole to place the chimney. The small cross-sectional area of the outlet hole and the cylindrical shape of the chamber cause some air to return to the outlet and temporarily entrap the exhaust gases and vapors. Underneath the biochar production chamber was a liquid petroleum gas (LPG) flame to provide the heat needed to carry out the process. Two gas valves were placed in the lower part of the apparatus to change the central and peripheral flame beneath the pyrolysis unit. A 48V high-speed ball bearing fan was used to change the exhaust air flow rate of the pyrolysis chamber. The fan was controlled by the ATMEGA32 microcontroller. The speed of the fan was calculated by the Hall-effect sensor, which was calculated with the microcontroller.

When the flame was ignited, the chamber was preheated to 350°C. Then, the weighted straw sample was placed on the bed. The air exit pipe was placed at the top of the chamber. Then the wheat straw samples were heated in the chamber at 450°C for 15 min for the pyrolysis and conversion to biochar. During the biochar production process by the oxidative method, some of the biomass was combusted, but the gases from the combustion of raw materials reduced the oxygen level and prevented the burning of the residual mass. The process was repeated by changing the speed of ventilation fan located at the bottom of the air exit pipe to change the exhaust air flow rate at four different levels of 20, 25, 30 and 35 $Lmin^{-1}$. To investigate the effect of temperature changes on the constant exhaust air flow rate (25 $Lmin^{-1}$), the straw samples were converted to biochar at temperatures of 350°C, 400°C, 450°C and 500°C. The effect of changes in temperature and outlet air flow rate on pH, yield, bulk density and ash was investigated. To determine the pH and bulk density of the samples, 0.2 g of each sample was mixed with 50 mL of distilled water at 25°C for 2 min by a magnetic stirrer. Then, the pH value was determined with the portable ATC 98108 pH meter made in Taiwan with 0.01 accuracy. The yield of the biochar production apparatus, which is the weight of produced biochar per unit of dry weight of biomass, was calculated by the following formula (Song and Guo, 2012):

$$Yeild(\%) = \frac{Weight\ of\ biochar\ (g)}{Dry\ weight\ of\ biomass\ (g)} \times 100 \tag{1}$$

The amount of ash was measured according to ASTM D-2866 standard method as (Song and Guo, 2012):

$$Ash(\%) = \frac{Weight\ of\ ash\ (g)}{Dry\ weight\ of\ biochar\ (g)} \times 100 \quad (2)$$

The bulk density was obtained by dividing the unit mass of the material by the unit volume. The bulk density of the samples was measured according to ASTM D-285 method. The bulk density was calculated by Equation 3 (Song and Guo, 2012). All statistical analyses were performed using SAS 9.1.3 software.

$$Bulk\ Density\ (g\ cm^{-3}) = \frac{Weight\ of\ biochar\ (g)}{Volume\ of\ biochar\ (cm^3)} \times 100 \quad (3)$$

3 Results and discussion

After fabricating the apparatus, it was evaluated for biochar production from wheat straw. The images of the some produced biochars are shown in Figure 2.

Figure 2 The produced biochars samples

A summary of the mean measured values of biochar properties is shown in Table1. The comparison of treatment was done by Duncan test at level of 5% probability. According to the results of Table 1, the mean values of pH and ash content were increased significantly with increasing air flow rate and air chamber temperature, while these results for yield and bulk density parameters occurred in decreasing trend.

Table 1 The mean values of measured parameters of produced biochar

Treatments	Mean values			
Air flow rate ($Lmin^{-1}$)	pH	Yield (%)	Ash content (%)	Bulk density ($g\ cm^{-3}$)
20	8.10^{d*}	50^{a*}	40^{d*}	0.19^{a*}
25	8.20^{c*}	35^{b*}	51^{c*}	0.18^{ab*}
30	8.80^{b*}	32^{c*}	58^{b*}	0.16^{bc*}
35	9.40^{a*}	25^{d*}	71^{a*}	0.14^{c*}
Air chamber temperature (°C)				
350	8.37^{c*}	50^{a*}	40^{d*}	0.19^{a*}
400	8.80^{c*}	47^{b*}	55^{c*}	0.17^{a*}
450	9.30^{b*}	42^{c*}	62^{b*}	0.14^{b*}
500	10.20^{a*}	38^{d*}	66^{a*}	0.11^{c*}

Note: *Significant (5% level)

3.1 pH variation

The variation of pH for produced biochar versus the outlet air flow rate is shown in Figure 3. According to the results, the pH values for the flow rates of 20, 25, 30 and 35 $Lmin^{-1}$ were 8.1, 8.2, 8.8 and 9.4, respectively. As seen, the pH values increased by increasing the air flow rate. Increasing the out air flow rate of the chamber (because of the providing more oxygen), will increase the combustion of the biomass and therefore release the more energy in the chamber as heat. Hence the temperature of the chamber and biomass will increase. This phenomenon will accelerate the separation the mineral parts of biochar from the organic part, consequently the pH values is increased.

The variation of pH values versus the temperature chamber is shown in Figure 4. The results showed that the pH values of the produced biochar samples at the temperatures of 350°C, 400°C, 450°C and 500°C were

8.1, 8.8, 9.3 and 10.2, respectively, which changed with an increasing trend. The reason for the increasing pH with increasing temperature is the separation of biochar minerals from its organic fraction at the temperatures above 350°C (Taketani and Tsai, 2010). Structurally, the pH of biochar depends on the pyrolysis method. Usually, the lower pyrolysis temperature, the lower pH is achieved, because of the remaining of carboxyl and hydroxyl groups on its structure.

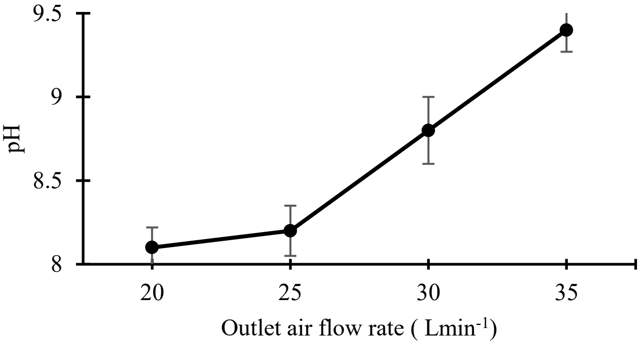

Figure 3 pH variation for different outlet air flow rate at temperature of 350°C

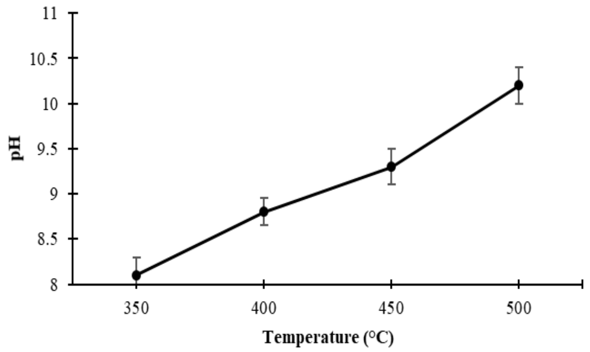

Figure 4 pH variation for different air chamber temperature at outlet air flow rate of 20 $Lmin^{-1}$

In a study, an increase in the pH of biochar produced from poultry manure was reported with increasing the process temperature from 300°C to 600°C (Song and Guo, 2012). In a conducted research by Gaskin et al. (2008), the biochars produced from poultry manure, peanut shell and pine wood at 400°C had the pH values of 10.1, 10.5 and 7.6, respectively. The effect of increasing pyrolysis temperature on pH increases has also been reported for the rice husk biochar (Claoston et al., 2014). Increasing the salt levels will make the biochar alkaline. The pyrolysis unit conditions also play an important role in the pH of produced biochar. The lower temperatures will product acidic biochar (Amonette and Joseph, 2009). In acidic soils, biochar can be used because of having calcium carbonate to increase soil pH and alkalinity (Chan et al., 2007).

3.2 Yield variation

The variation yield of produced biochar for different outlet air flow rates is shown in Figure 5. As can be seen, in the range of tested flow rates, the yield varied between 25% to 50% with decreasing trend.

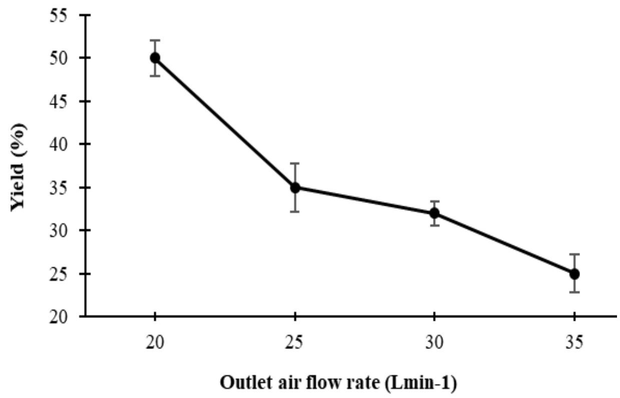

Figure 5 Yield variation for different outlet air flow rate at temperature of 350°C

Also, the yield of biochar production at the temperatures of 350°C, 400°C, 450°C and 500°C were 51%, 47%, 42% and 38%, respectively (Figure 6). Based on the literature, the biochar yield production depends on the cellulose degradation reactions and biomass polymerization process (Demirbaş, 2001). At low temperatures, biochar has a higher yield due to the lower emission of methane, hydrogen, carbon dioxide gases and the lower density of aliphatic compounds (Amonette and Joseph, 2009). According to the literature, one of the causes of yield loss at high temperature is the thermal decomposition of lignocellulose (Antal and Gronli, 2003). The water existing in the biomass is evaporated at high temperatures (above 120°C) and the organic matter is decomposed by heat. The amount of lignin present in the biochar raw material is directly related to yield (Sohi et al., 2010). In a similar study, the reason for the decrease in the yield of rice husk biochar with increasing temperature was the primary and secondary degradation of residual biochar at higher temperatures (Horne and Williams, 1996). In another research, the decrease in yield of biochar produced from pine wood was reported (Wang et al., 2012).

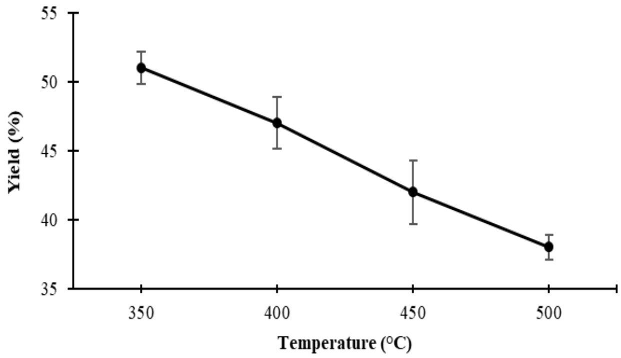

Figure 6 Yield variation for different air chamber temperature at outlet air flow rate of 20 $Lmin^{-1}$

3.3 Ash content variation

Increasing the percentage of minerals and thermal decomposition of lignocellulose materials will increase the amount of produced biochar ash (Cao et al., 2009). The increase in the amount of produced ash during the pyrolysis process indicates the higher level of nutrients. The forage biomass produces more ash than woody biomass, which indicates the higher nutrient content.

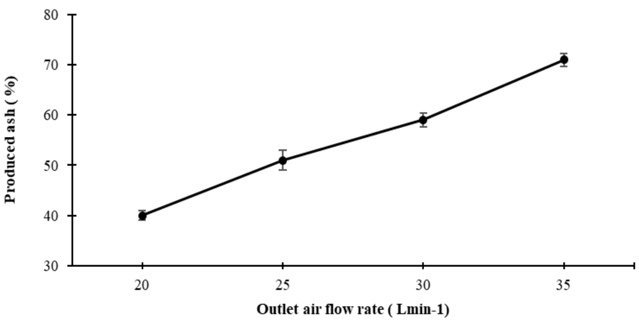

Figure 7 Produced ash variation for different outlet air flow rate at temperature of 350°C

It should be noted that the colloidal particles of soil can be attached to biomass and contaminate the raw material during the experiment (Cao et al., 2009). According to the results of this study, the amount of oxidation biochar ash increased with increasing the outlet air flow rate. The curve of changes in percentage of produced ash in versus of air flow rate changes is shown in Figure 7. Based on the results, the amount of ash produced from the wheat straw biochar increased from 40 to 71%. The liming power of biochar depends basically on its ashes content. Ash content of biochar is very variable and depends on different parameters. And the liming effect of the biochar ashes depends on its bases content (Ca, Mg, K and Na).

The results showed that the amount of produced ash increased with increasing the chamber temperature (Figure 8). This increase is due to the increasing of the percentage of biochar carbon, as the evaporation is higher during the pyrolysis process with increasing temperature. In general, the increase in biochar ash is due to the increasing in the amount of elements during the pyrolysis process. In a similar study, the increase in ash content in the pine wood biochar was reported in the temperature range between 300 and 500 °C (Wang et al., 2012). In another research, the increasing in the concentration of minerals and the thermal degradation of lignocellulosic materials are reported as the reason for increasing ash content (Taketani and Tsai, 2010).

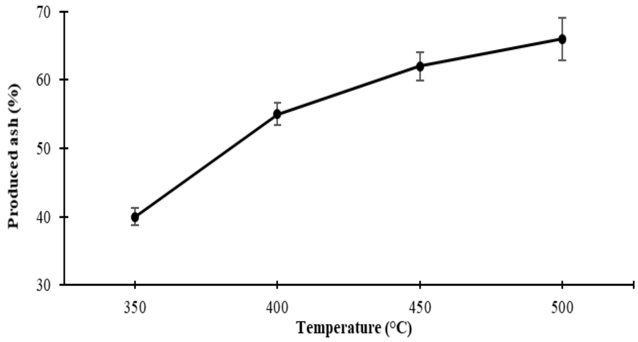

Figure 8 Ash content variation for different air chamber temperature at outlet air flow rate of 20 $Lmin^{-1}$

3.4 Bulk density variation

The density of produced biochar depends on the nature of the raw material and the pyrolysis process (Hwang et al., 2007).

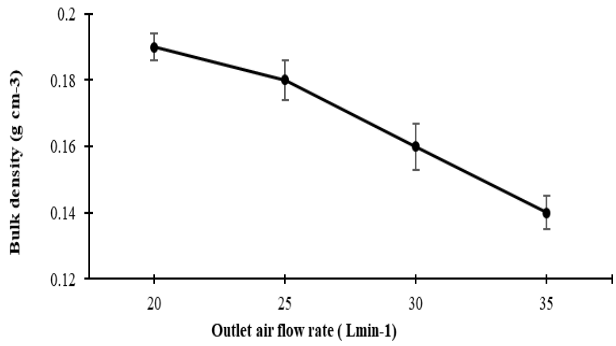

Figure 9 Bulk density variation for different outlet air flow rate at temperature of 350°C

According to the results of this study, the bulk density of oxidation biochar of wheat straw at different levels of chamber air flow rate changed between 0.14 and 0.19

(Figure 9) and at different temperatures of chamber air temperature between 0.11 to 0.19 g cm^{-3} (Figure 10). In a similar study, the bulk density of biochar produced from wood in the traditional furnace changed in the range of 0.3 to 43 g cm^{-3}, but did not show any specific trend with increasing the temperature (Mohan et al., 2006).

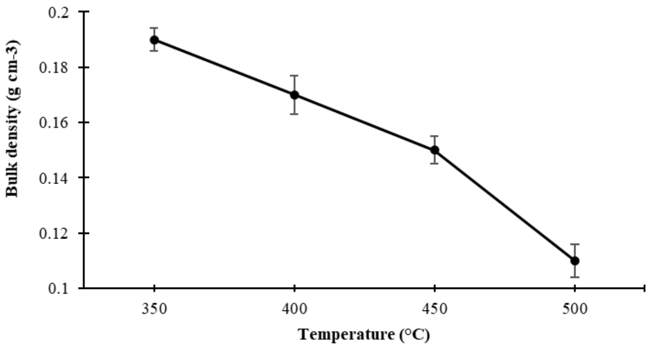

Figure 10 Bulk density variation for different air chamber temperature at outlet air flow rate of 20 $Lmin^{-1}$

4 Conclusions

From the above discussion it can be concluded that:

1) The outlet air flow rate and temperature of the chamber influenced the pH, ash, yield and density

2) The pH values ranged from 8.1-9.4 and 8.1-10.2 for different of air flow rates and chamber temperature, respectively with increasing trends.

3) The yield was varied from 25%-50% and 38%-51% for different of air flow rates and chamber temperature, respectively with decreasing trends.

4) The amount of ash increased from 40% to 71% and 40% to 66%, for different air flow rates and air chamber temperature.

5) The bulks density values ranged from 0.14-0.19 and 0.11- 0.19 for different of air flow rates and chamber temperature, respectively with decreasing trends.

Acknowledgment

The financial support provided by the Razi University is duly acknowledged.

References

Ahmad, M., A. U. Rajapaksha, J. E. Lim, M. Zhang, N. Bolan, D. Mohan, M. Vithanage, S. S. Lee, and Y. S. Ok. 2014. Biochar as a sorbent for contaminant management in soil and water: a review. *Chemosphere*, 99: 19-33.

Amonette, J., and S. Joseph. 2009. Characteristics of biochar: microchemical properties. In *Biochar for Environmental Management: Science and Technology*, ch. 3, 33-52. London: Earthscan.

Antal, M. J., and M. Grønli. 2003. The art, science, and technology of charcoal production. *Industrial & Engineering Chemistry Research*, 42(8): 1619-1640.

Basu, P. 2010. *Biomass Gasification and Pyrolysis: Practical Design and Theory*. Academic Press: Elsevier.

Bridgwater, A. V. 2003. Renewable fuels and chemicals by thermal processing of biomass. *Chemical Engineering Journal*, 91(2-3): 87-102.

Cao, X., L. Ma, B. Gao, and W. Harris. 2009. Dairy-manure derived biochar effectively sorbs lead and atrazine. *Environmental Science & Technology*, 43(9): 3285-3291.

Chan, K. Y., L. Van Zwieten, I. Meszaros, A. Downie, and S. Joseph. 2007. Agronomic values of green waste biochar as a soil amendment. *Australian Journal of Soil Research*, 45(8): 629-634.

Claoston, N., A. W. Samsuri, M. H. A. Husni, and M. S. M. Amran. 2014. Effects of pyrolysis temperature on the physicochemical properties of empty fruit bunch and rice husk biochars. *Waste Management and Research*, 32(4): 331-339.

Daouk, E., L. Van de Steene., F. Paviet, and S. Salvador. 2015. Thick wood particle pyrolysis in an oxidative atmosphere. *Chemical Engineering Science*, 126: 608-615.

Demirbaş, A. 2001. Biomass resource facilities and biomass conversion processing for fuels and chemicals. *Energy Conversion and Management*, 42(11): 1357-1378.

Devi, P., and A. K. Saroha. 2013. Effect of temperature on biochar properties during paper mill sludge pyrolysis. *International Journal of ChemTech Research*, 5(2): 682-687.

Di Blasi, C. 2008. Modeling chemical and physical processes of wood and biomass pyrolysis. *Progress in Energy and Combustion Science*, 34(1): 47-90.

Gaskin, J. W., C. Steiner, K. Harris, K. C. Das, and B. Bibens. 2008. Effect of low-temperature pyrolysis conditions on biochar for agricultural use. *Transaction of the ASABE*, 51(6): 2061-2069.

Horne, P. A., and P. T. Williams. 1996. Influence of temperature on the products from the flash pyrolysis of biomass. *Fuel*, 75(9): 1051-1059.

Hwang, I. H., Y. Ouchi, and T. Matsuto. 2007. Characteristics of leachate from pyrolysis residue of sewage sludge. *Chemosphere*, 68(10): 1913-1919.

Javdani Soodi, S., A. Lakziyan, and R. Khorasani. 2012. Effect of biochar on the concentration of mineral forms of nitrogen in acidic soil. In *Iranian Soil Congress*, *Malayar University, Malayer*. 12-23 (In Persian).

Laird, D., P. Fleming, B. Wang, R. Horton and D. Karlen. 2010. Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma*, 158(3-4): 436-442.

Milhé, M., L. van de Steene, M. Haube, J. M. Commandré, W. F. Fassinou, and G. Flamant. 2013. Autothermal and allothermal pyrolysis in a continuous fixed bed reactor. *Journal of Analytical and Applied Pyrolysis*, 103: 102-111.

Mohan, D., C. U. Pittman Jr, and P. H. Steele. 2006. Pyrolysis of wood/biomass for bio-oil: a critical review. *Energy and Fuels,* 20(3): 848-889.

Sobhaniyan Nezhad, L. 2011. Evaluation of land use type on some soil qualitative indices in northwest of khuzestan province. M.S. thesis, Sahid Chamran University of Ahvaz (In Persian).

Sohi, S. P., E. Krull, E. Lopez-Capel, and R. Bol. 2010. A review of biochar and its use and function in soil. *Advances in Agronomy,*105: 47-82.

Song, W., and M. Guo. 2012. Quality variations of poultry litter biochar generated at different pyrolysis temperatures. *Journal of Analytical and Applied Pyrolysis*, 94: 138-145.

Taketani, R. G., and S. M. Tsai. 2010. The influence of different land uses on the structure of archaeal communities in amazonian anthrosols based on 16S rRNA and amoA Genes. *Microbial Ecology*, 59(4): 734-743.

Tomczyk, A., Z. Sokołowska, and P. Boguta. 2020. Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. *Reviews in Environmental Science and Bio/Technology*, 19(1): 191-215.

Wang, T., M. Camps-Arbestain, M. Hedley, and P. Bishop. 2012. Predicting phosphorus bioavailability from high- ash biochars. *Plant and Soil*, 357(1): 173-187.

Wolf, D., J. E. Amonette, F. A. Street-Perrott, J. Lehmann, and S. Joseph. 2010. Sustainable biochar to mitigate global climate change. *Nature Communications*, 1(1): 56.

Wu, F., Z. Jia, S. S. Wang, S. X. Chang, and A. Startse. 2013. Contrasting effects of wheat straw and its biochar on greenhouse gas emissions and enzyme activities in a Chernozemic soil. *Biology and Fertility of Soils*, 49(5): 555-565.

Zhang, L., B. Song, and B. Chen. 2012. Energy-based analysis of four farming systems: insight into agricultural diversification in rural China. *Journal of Cleaner Production*, 28: 33-44.