



Original Research Article

A Study on the Impact of Temperature and Residence Time on the Torrefaction of Rice Husk and Sawdust

*¹Usman, M.M., ²Garba, M.U., ²Manaseh, A. and ²Saka, A.A.

¹Department of Chemical Engineering Technology, The Federal Polytechnic, Nasarawa, Nasarawa State, Nigeria.

²Department of Chemical Engineering, Federal University of Technology, Minna, Niger State, Nigeria.

*murtala_usman@yahoo.com

<http://doi.org/10.5281/zenodo.5805394>

ARTICLE INFORMATION

Article history:

Received 10 Nov, 2021

Revised 07 Dec, 2021

Accepted 08 Dec, 2021

Available online 30 Dec, 2021

Keywords:

Torrefaction

Biomass

Residence-time

Temperature

Carbonisation

ABSTRACT

The use of fossil fuels such as coal has negative impacts on the environment. Biomass-based fuels will have a better sustainability footprint when compared to fossil fuels. In this study, biomass with little value which usually ends up as waste that constitute environmental pollution was used to produce energy-rich products through torrefaction. This study evaluates the impact of temperature and residence time on torrefaction of rice husk and sawdust respectively. The properties of the produced materials were determined through proximate analysis, ultimate analysis, and calorific value. Fixed carbon content from the proximate analysis showed an increase of 13.40% between the rice husk products (TRH300 and TRH350), produced at 300 and 350 °C respectively, while an increase of 2% was recorded for sawdust products, TSD15 and TSD20, produced at 15 and 20 minutes respectively. Volatile contents decreased with an increase in temperature and residence time. Ultimate analysis results showed an increase of 8.22% in elemental carbon for TRH300 to TRH350, and 3.1% for TSD15 to TSD20 respectively. The oxygen contents decreased as temperature and residence time were increased. The calorific value showed an increase of 6.29% for TRH300 to TRH350, and 3.04% for TSD15 to TSD20 respectively, with increased temperature and residence time.

© 2021 RJEES. All rights reserved.

1. INTRODUCTION

The problem of global warming and waste generation require engineering solutions that can turn waste into energy and thereby curtail global warming. Fossil fuels pose serious environmental threats and poses a high global warming potential while biomass-based fuels have a better sustainability footprint when compared to

fossil fuels (Akhtar *et al.*, 2021). Energy from agricultural biomass has been accepted as a promising alternative to fossil fuels which has resulted in many advancements and researches for biomass conversion technologies (Okekunle *et al.*, 2020). These biomass materials are mostly lignocellulosic and their major disadvantages when utilizing them as energy sources are high oxygen content, low calorific value, low energy density, hydrophilic nature and high moisture content, low bulk energy density, poor grindability, susceptibility to deterioration, and microbial and fungal attacks during storage (Bartha-Rajnai *et al.*, 2017, Kanwal *et al.*, 2019; Akhtar *et al.*, 2021).

Torrefaction is a thermochemical pre-treatment process that is carried out at temperatures ranging between 200-300 °C under various operating conditions such as residence and heating rates to improve those disadvantages possessed by raw biomass (Akhtar *et al.*, 2021, Barta-Rajnai *et al.*, 2017). It is a form of slow pyrolysis in an inert atmosphere carried out to improve the physicochemical properties of biomass, to maximize solid yield (biochar) for energy use (Kanwal *et al.*, 2019; Li *et al.*, 2012). To avoid oxidation and achieve high thermal degradation, nitrogen is usually used to provide the required inert atmosphere (Garba *et al.*, 2017). As a developing area of intense interest, torrefaction is envisaged to become a leading technology, motivating many studies in this area (Garba *et al.*, 2017).

As a lot of biomass materials are widely available with little economic value that eventually turns out to be solid waste and their disposal constitutes environmental pollution. Also, with environmental issues such as global warming due to increased carbon footprint emanating from non-renewable energy sources such as fossil-based fuels, these biomass materials are one of the most abundant renewable sources to produce biofuels (Chen *et al.*, 2021; Mohamed *et al.*, 2019). The production of torrefied materials from these biomasses will help in the reduction of solid waste generation thereby preventing further secondary pollution that could arise from burning them as waste. The torrefied biomass has a lower oxygen content, larger calorific value and higher carbon content than the raw biomass (Cen *et al.*, 2020).

Compared to the temperature, the residence time may also have an important effect on the physicochemical of torrefied materials (Cen *et al.*, 2020). It is crucial to study their relationships as increasing torrefaction temperature adds to the operating cost. Thus, this paper aims to evaluate the impact of temperature and residence time on the production of torrefied rice husk and sawdust respectively, and to characterize the torrefied products through proximate analysis, ultimate analysis, and calorific value.

2. MATERIALS AND METHODS

2.1. Raw Material

Rice husk and sawdust were obtained from local rice and wood mills respectively, at Tammah, Nasarawa, Nasarawa State, Nigeria. Each sample was washed with running tap water and then distilled water to remove dirt and impurities before sun drying for about 4-5 days at an ambient temperature of about 30-35 °C.

2.2. Torrefaction Procedure

Both rice husk and sawdust samples were manually crushed with a mallet and sieved using standard 150 and 75 µm sieves to obtain definite particle sizes. The samples were then dried in an oven (Gallenkamp, England) at 105 °C for 6 hours, packed in polyethylene bags, and stored in airtight plastic containers before torrefaction. A muffle furnace (tlx 59388, Gemco, Holland) was utilized for the torrefaction process. Two (2) samples each weighing 10 g of the oven-dried rice husk samples were weighed separately into crucibles and placed in the furnace. Both the furnace and crucible were purged with nitrogen (N₂) to ensure an inert atmosphere before starting the furnace. The 2 samples were torrefied at 300 and 350 °C under constant residence time (15 minutes) and heating rate (20 °C/minute), producing 2 products, named TRH300 and TRH350 after their torrefaction temperature respectively. A similar procedure was applied for the sawdust but was torrefied at two (2) residence times of 15 and 20 minutes under a constant temperature of 300 °C and heating rate of 20 °C/minute. The products were named TSD15 and TSD20 respectively. All the torrefied products were packed in polyethylene bags and stored in airtight plastic containers before characterisation.

2.3. Characterisation

The proximate analysis, ultimate analysis, and calorific values of the produced torrefied materials (TRH300, TRH350, TSD15, and TSD20) and their feedstocks (non-torrefied) i.e., raw rice husk (RRH) and raw sawdust (RSD) were determined for comparison.

2.3.1. Proximate analysis

This was conducted according to the American Society for Testing and Materials (ASTM) D3173-75 (ASTM, 2002; ASTM, 2007; ASTM; 2008) standard procedures and the details are given in the following sections.

2.3.1.1. Moisture content

Exactly 1 g of the sample was measured in a crucible and heated in an oven for about 1 hour at 105 °C and then cooled in a desiccator (ASTM, 2008). The loss in weight of the samples was determined and the moisture content (MC) was determined using Equation (1).

$$MC (\%) = \left(\frac{W_2 - W_3}{W_2 - W_1} \right) \times 100 \quad (1)$$

Where W_1 is the weight of crucible (g); W_2 is the weight of crucible and sample (g); W_3 is the weight of crucible and sample after heating (g).

2.3.1.2. Volatile content

The dried samples were heated in a lid-covered crucible at 600 °C for 6 minutes and then at 900 °C for another 6 minutes (ASTM, 2007). The volatile contents (VC) are then determined using Equation (2).

$$VC (\%) = \left(\frac{W_4 - W_6}{W_5 - W_1} \right) \times 100 \quad (2)$$

Where W_4 is the weight of crucible and sample before oven drying (g); W_5 is the weight of crucible and sample before keeping in a muffle furnace (g); W_6 is the weight of crucible and sample after keeping in a muffle furnace (g).

2.3.1.3. Ash content

The sample that remains in the crucible during the determination of VC was further heated without the lid in a muffle furnace at 750 °C for 30 minutes. The crucible was then cooled first in the air, then in desiccators, and the weight was recorded with the process repeated until a constant weight was obtained (ASTM, 2002). The ash content (AC) was calculated using Equation (3).

$$AC (\%) = \left(\frac{W_8 - W_9}{W_7 - W_1} \right) \times 100 \quad (3)$$

Where W_7 is the weight of crucible and sample before oven drying (g); W_8 is the weight of crucible and sample before placing in a muffle furnace (g); W_9 is the weight of crucible and sample after placing in a muffle furnace (g).

2.3.1.4. Fixed carbon

The fixed carbon (FC) was calculated based on the difference of the sum of moisture, volatile, and ash contents using Equation (4).

$$FC (\%) = 100 - \% (MC + VC + AC) \quad (4)$$

2.4. Ultimate Analysis

The carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulphur (S) contents were determined using a CHNS elemental analyser (Flash 2000, Thermo Fisher Scientific Inc., USA) through a high temperature

catalysed combustion followed by infrared detection of the generated CO₂, H₂, NO₂, and SO₂ respectively. The oxygen (*O*) contents were determined by mass balance using Equation (5), assuming the total weight fraction of all measured elements sum up to one (1).

$$O = 100 - \% (C + H + N + S + \text{ash content}) \quad (5)$$

2.5. Calorific Value

The calorific values (CV) of the samples were determined using a bomb calorimeter connected to an oxygen cylinder at a pressure of 207 kPa. Exactly 1 g of each sample was weighed into a cleaned dried capsule, placed in a crucible within the calorimeter, and then closed tightly. The determined calorific value was then recorded.

3. RESULTS AND DISCUSSION

3.1. Proximate Analysis

The results of the proximate analysis are presented in Tables 1 and 2 for both rice husk and sawdust respectively.

Table 1: Proximate analysis of RRH, TRH300, and TRH350

S/N	Sample	Moisture content (%)	Ash content (%)	Volatile content (%)	Fixed carbon (%)
1	RRH	17.92	12.34	53.93	15.81
2	TRH300	12.15	19.27	35.38	33.20
3	TRH350	9.14	22.00	30.52	38.34

For a material to be used as a fuel, carbon content is the most desired (Dai *et al.*, 2019). It is a measure of non-volatile carbon remaining in the material. The fixed carbon content which is the combustible carbon that remains after the volatile content has been expelled increased significantly from 15.81% of the RRH feedstock to 33.20% when it was torrefied at 300 °C under constant residence time of 15 minutes and a heating rate of 20 °C/minute. This represents an increase of about 47.62% for TRH300. As the temperature was further increased to 350 °C, the fixed carbon content increased again to 38.34% for TRH350, which is a percentage increase of about 13.40 between the two (2) produced products. As expected, the moisture contents have generally decreased as a resulting of torrefaction temperature because higher temperatures dry materials.

The volatile contents also decreased with an increase in temperature. This could be attributed to the thermal volatilization of components of the feedstock such as lignin, cellulose, and hemicellulose. The RRH had a volatile content of 53.93% but reduced to 35.38 and 30.52 for TRH300 and TRH350 respectively. This shows that with temperature increase, more volatile contents can be driven off in favour of higher fixed carbon contents. The ash contents increased as shown in Table 1. According to Phanphanich and Mani, (2011), this could be attributed to the loss of organic matter during the process of torrefaction. Ash forming elements are mostly iron oxides, calcium carbonate, potassium silicates, etc. The ash content is characterized by the presence of large amounts of alkaline and alkaline earth metals such as sodium, potassium, and calcium (Garba *et al.*, 2017).

A similar trend in the results for sawdust was obtained as shown in Table 2 when torrefied under the two-residence time of 15 and 20 minutes respectively. The fixed carbon content increased from 37.38 to 38.14% for TSD15 and TSD20. This represents a percentage increase of just about 2% and could be attributed to inadequate residence time for enough carbonisation to take place. Sawdust possesses a more volatile content of 77.49% compared to rice husk with 53.93%. Similarly, it can be observed that the volatile content decreased to 51.46 and 49.17% for TSD15 and TSD20 respectively. This can also be credited to the volatilization of the volatile components present in the raw sawdust feedstock.

Table 2: Proximate analysis of RSD, TSD15, and TSD20

S/N	Sample	Moisture content (%)	Ash content (%)	Volatile content (%)	Fixed carbon (%)
1	RSD	7.20	3.20	77.49	12.11
2	TSD15	6.00	5.15	51.46	37.38
3	TSD20	5.50	7.19	49.17	38.14

Likewise, the ash contents increased from 3.20% of the RSD feedstock to 5.15 and 7.19% for TSD15 and TSD20 respectively. A similar reason to the case of rice husk can be attributed to this which is the loss of organic contents during the process. Generally, as torrefaction enriches the carbon content and reduces the volatile contents, the ash content increases. The moisture content has decreased but not significantly from 7.20% for RSD to 6.0 and 5.5% for TSD15 and TSD20 respectively.

3.2. Ultimate Analysis

The results of ultimate analysis, also known as elemental analysis because it gives the carbon (C), hydrogen (H), nitrogen (N), and oxygen (O) compositions are presented in Tables 3 and 4 for rice husk and sawdust respectively.

Table 3: Ultimate analysis of RRH, TRH300, and TRH350

S/N	Sample	C (%)	H (%)	N (%)	O (%)	S (%)
1	RRH	48.14	5.10	0.82	44.70	0.16
2	TRH300	56.17	4.21	0.60	37.89	0.19
3	TRH350	61.20	3.90	0.41	34.10	0.21

The carbon content from the ultimate analysis is also known as total carbon because it includes some organic carbon. It can be seen from Tables 3 and 4 that the carbon contents both increased as a result of torrefaction temperature and residence time for rice husk and sawdust respectively. The RRH with 48.14% increased to 56.17 and 61.20% for TRH300 and TRH350 respectively. This amounts to a percentage increase of 8.22% in carbon content as the temperature was increased from 300 to 350 °C. Likewise, from Table 4, the impact of the residence time of 15 and 20 minutes on sawdust showed a similar pattern. The RSD feedstock with 41.66% increased to 57.84 and 59.69% for TSD15 and TSD20 respectively. This represents about a 3.1% increase. This could be attributed to the formation and release of CO, CO₂, and water vapours (Phanphanic and Mari, 2011; Li *et al.*, 2012) or related to increased volatilization of these surface functional group elements into CO₂ or CO during the torrefaction process (Agrafioti *et al.*, 2013). The results of this study are comparable to that obtained by (Mohamed *et al.*, 2019).

Table 4: Ultimate analysis of RSD, TSD15, and TSD20

S/N	Sample	C (%)	H (%)	N (%)	O (%)	S (%)
1	RSD	41.66	7.63	0.37	50.22	0.12
2	TSD15	57.84	4.92	0.44	36.60	ND
3	TSD20	59.69	5.07	0.56	34.68	ND

ND Stands for “Not Detected”

There was a very noticeable and similar decrease in the oxygen contents from both RRH and RSD feedstocks compared to the produced materials under varying temperatures and residence times as shown in Tables 3 and 4. There was a 5.25% difference in oxygen content between TSD15 and TSD20 as the residence time was increased from 15 to 20 minutes while a difference representing about 10% was recorded between TRH300 and TRH350 when the temperature increased from 300 to 350 °C respectively. A biomass material typically comprises labile and recalcitrant O fractions; the former is rapidly lost after the heating, while the latter is retained in the char of the final product (Rutherford *et al.*, 2005). Similarly, the hydrogen contents also decreased as shown in Tables 3 and 4 respectively, and this is also attributed to the loss of volatile products such as CO, CO₂, and water (Park *et al.*, 2013).

3.3. Calorific Value

The results for the calorific values are presented in Figures 1 and 2 which clearly show a very similar trend of increase in value as the RRH and RSD feedstocks were been torrefied at varying temperature and residence time respectively. From Figure 1, there was about 6.29% increase in the calorific value as the torrefaction temperature was increased from 300 to 350 °C for TRH300 and TRH350 respectively. In the work of Chen *et al.* (2021), similar results were obtained. Similarly, from Figure 2 it can observe that the calorific value increased only slightly by a difference of 3.04% from TSD15 and TSD20 when the residence time was increased from 15 to 20 minutes. This result is comparable to what was obtained by Agrafioti *et al.*, (2013) and Lunguleasa *et al.*, (2019).

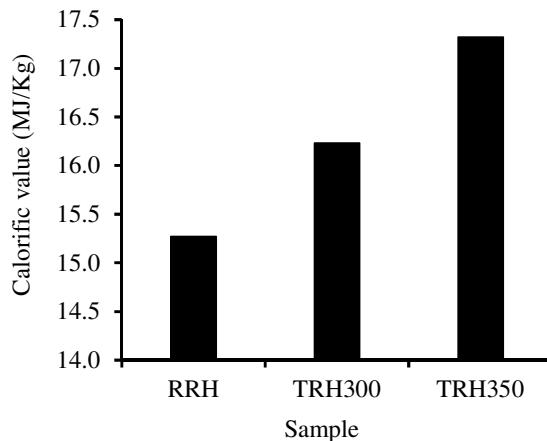


Figure 1: Calorific value of RRH, TRH300, and TRH350 respectively

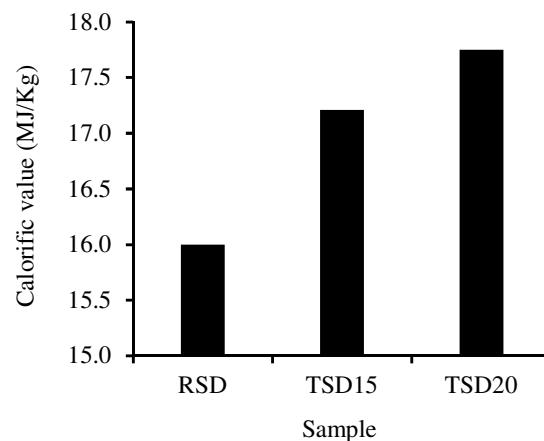


Figure 2: Calorific value of RSD, TSD15, and TSD20 respectively

4. CONCLUSION

The impact of torrefaction temperature and residence of two (2) different biomass materials on the physicochemical properties of produced torrefied materials have been evaluated in this study. The result in nearly all examined cases revealed that increased temperature and residence time favours better properties such as calorific values, fixed and elemental contents, etc. The results, however, showed that increased torrefaction temperature produces better properties compared to increasing the residence time.

5. ACKNOWLEDGMENT

The authors wish to acknowledge the assistance of the staff of Unit Operation Laboratories of the Department of Chemical Engineering Technology, The Federal Polytechnic, Nasarawa, and that of Department of Chemical Engineering, Federal University of Technology, Minna, for their contributions towards the success of this work.

6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

REFERENCES

- Agrafioti, E., Bouras, G., Kalderis, D. and Diamadopoulos, E. (2013). Biochar production by sewage sludge pyrolysis. *Journal of Analytical and Applied Pyrolysis*, 101, pp. 72–78.

- Akhtar, J., Imran, M., Ali, A.M., Nawaz, Z., Muhammad, A., Butt, R.K., Jillani, M.S., and Naeem, H. A. (2021). Torrefaction and thermochemical properties of agriculture residues. *Energies*, 14(4218), pp. 1–13.
- ASTM (2002). *Test Method for Ash Content in the Analysis Sample of Coal and Coke* (D3174). Retrieved from: <https://www.astm.org/>
- ASTM (2007). *Test Method for Volatile Matter in the Analysis Sample of Coal and Coke* (D3175). Retrieved from: <https://www.astm.org/>
- ASTM (2008). *Test Method for Moisture in the Analysis Sample of Coal and Coke* (D3173). Retrieved from: <https://www.astm.org/>
- Barta-Rajnai, E., Wang, L., Sebestyén, Z., Barta, Z., Khalil, R., Skreiberg, O., Grønli, M., Jakab, E. and Czégény, Z. (2017). Effect of temperature and duration of torrefaction on the thermal behavior of stem wood, bark, and stump of spruce. *Energy Procedia*, 105, pp. 551–556.
- Cen, K., Zhang, J., Chen, D., Chen, F., Zhang, Y. and Ma, H. (2020). Comparative study of the fuel quality and torrefaction performance of biomass and its molded pellets: effects of temperature and residence time. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, pp. 1–10.
- Chen, C., Ji, G., Mu, L., Zhang, Y., and Li, A. (2021). Comprehensive research on the solid, liquid, and gaseous products of rice husk and rice straw torrefaction. *Sustainable Energy & Fuels*, 5(687), pp. 687–697.
- Dai, L., Wang, Y., Liu, Y., Ruan, R., He, C., Yu, Z., Jiang, L., Zeng, Z., and Tian, X. (2019). Integrated process of lignocellulosic biomass torrefaction and pyrolysis for upgrading bio-oil production: A state-of-the-art review. *Renewable and Sustainable Energy Reviews*, 107(1), pp. 20–36.
- Garba, M.U., Gambo, S.U., Musa, U., Tauheed, K., Alhassan, M., Adeniyi, O.D., Gambo, S.U., Musa, U., Tauheed, K., Alhassan, M., and Adeniyi, O.D. (2017). Impact of torrefaction on fuel property of tropical biomass feedstocks. *Biofuels*.
- Kanwal, S., Chaudhry, N., Munir, S. and Sana, H. (2019). Effect of torrefaction conditions on the physicochemical characterization of agricultural waste (sugarcane bagasse). *Waste Management*, 88, pp. 280–290.
- Li, H., Liu, X., Legros, R., Bi, X.T., Lim, C.J. and Sokhansanj, S. (2012). Torrefaction of sawdust in a fluidized bed reactor. *Bioresource Technology*, 103(1), pp. 453–458.
- Lunguleasa, A., Ayrilmis, N., Spirchez, C. and Croitoru, C. (2019). Increasing the calorific properties of sawdust waste from pellets by torrefaction. *BioResources*, 14(4), pp. 7821–7839.
- Mohamed, A.R., Nordin, N.N.A. and Salleh, N.H.M. (2019). Chemical properties of torrefied and raw sawdust. *Journal of Advanced Research in Engineering Knowledge*, 6(1), pp. 7–14.
- Okekunle, P.O., Maduekwe, S., Ajadi, G.S. and Olugbemisoye, S.A. (2020). Effect of temperature and residence time on torrefaction characteristics of African Birch (*Anogeissus leiocarpa*). *Covenant Journal of Engineering Technology*, 4(2), pp. 43–49.
- Park, J., Meng, J., Lim, K.H., Rojas, O.J. and Park, S. (2013). Transformation of lignocellulosic biomass during torrefaction. *Journal of Analytical and Applied Pyrolysis*, 100, pp. 199–206.
- Phanphanich, M. and Mani, S. (2011). Impact of torrefaction on the grindability and fuel characteristics of forest biomass. *Bioresource Technology*, 102(2), pp. 1246–1253.
- Rutherford, D.W., Wershaw, R.L. and Cox, L.G. (2005). *Changes in composition and porosity occurring during the thermal degradation of wood and wood components* (No. 2004-5292). United States Geological Survey.