Solar Torrefaction of Solid Olive Mill Residue

Nemika Cellatoğlu [a,b,*] and Mustafa İlkan [c]

Torrefaction is a thermochemical pretreatment method for improving fuel characteristics of biomass. The process is conducted between 200 and 300 °C under inert atmosphere. The relatively low process temperature of torrefaction makes the use of solar energy suitable with low costs. In this study, solid olive mill residue (SOMR) was used to test the feasibility of using solar energy in the torrefaction process. SOMR is an agricultural waste obtained from olive oil extraction, and it is mainly produced in the Mediterranean region, which has high solar energy potential. In this study, the torrefaction of SOMR was conducted by concentrating solar energy with a parabolic dish concentrator, at 250 °C for 10 min. The fuel properties of solar torrefaction products were compared with raw SOMR. Solar torrefaction yielded a deoxygenated solid fuel with increased carbon content and higher heating value (HHV), similar to torrefaction.

Keywords: Biomass; Solar Energy; Torrefaction; Pretreatment; Parabolic Dish Concentrator

Contact information: a: Department of Civil Engineering, European University of Lefke, Gemikonağı, Mersin 10, Turkey; b: Department of Physics, and c: School of Computing and Technology, Eastern Mediterranean University, Famagusta, Mersin 10, Turkey;
** Corresponding author: nemika.cellatoglu@emu.edu.tr*

INTRODUCTION

Biomass, mainly wood, is an important source of energy, which dominates 10% of the global energy supply (REN 21 2014). Biomass is directly combusted for energy generation. Besides hard and soft wood, agricultural residues are an important source of biomass.

Solid olive mill residue (SOMR) is an agricultural residue left over from olive oil extraction. SOMR mainly consists of water, seed, pulp, and olive stone (Doymaz *et al.* 2004; Gomez-Munoz *et al.* 2012). The main producers of SOMR are Mediterranean countries. It is estimated that 900 million olive trees cover over 10 million hectares worldwide (Sesli and Yeğenoğlu 2009), and Mediterranean countries produce approximately 2.5 million metric tons/year olive oil (Dermechea *et al.* 2013). During the olive oil extraction process, 200 kg of oil and 400 kg of SOMR is produced from each ton of olives (Sadeghi *et al.* 2010). Although direct combustion is a method for energy generation from biomass, a pretreatment or treatment to raw biomass results in more efficient energy generation.

Torrefaction is a thermochemical pretreatment of biomass that occurs at 200 to 300°C under inert atmosphere. Laboratory scale torrefaction experiments conducted with different types of biomass have shown that torrefaction improves the quality of biomass as a solid fuel (Brachi *et al.* 2016; Bridgeman *et al.* 2008; Rousset *et al.* 2011). Torrefied biomass contains less moisture (Felfri *et al.* 2005; Sadaka and Negi 2009), has increased energy density (Prins *et al.* 2006a; Yan *et al.* 2009; Rousset *et al.* 2011), and has increased higher heating value (HHV) (Bridgeman *et al.* 2008; Couhert *et al.* 2009; Deng *et al.* 2009;

Yan *et al.* 2009) compared to raw biomass. The effect of torrefaction on fast pyrolysis (Zheng *et al.* 2013), gasification (Sarkar *et al.* 2014), and carbonization (Cellatoğlu and İlkan 2016) characteristics of biomass has been studied as well. Zheng *et al.* (2013) showed an improved quality of bio-oil obtained from fast pyrolysis of corn cobs with torrefaction pretreatment. Sarkar *et al.* (2014) showed that torrefaction remarkably improved the gas yields, syngas lower heating value, and gasifier efficiencies (Sarkar *et al.* 2014). Cellatoğlu and İlkan (2016) showed that torrefaction contributed to reducing the holding time during carbonization.

The proven impacts of torrefaction on fuel characteristics of biomass have motivated commercial investments in torrefaction plants. Currently, a number of mostly European torrefaction initiatives have prompted construction and commissioning of the first commercial torrefaction plants (Deutmeyer *et al.* 2012). Natural gas or biomass is combusted for conducting torrefaction process in commercial plants.

The low process temperature relative to other biomass treatment methods makes solar energy very attractive for torrefaction (solar torrefaction). SOMR is suitable for the process because it is produced in the Mediterranean region, which enjoys the abundance of solar energy. Furthermore, SOMR is an attractive fuel for torrefaction (Cellatoğlu and İlkan 2015).

In this study, solar torrefaction of SOMR was tested with a parabolic dish collector. The results indicated that torrefaction process can be conducted with solar thermal energy and use of solar energy is promising for producing qualified solid fuel compared to raw biomass.

EXPERIMENTAL

SOMR torrefaction was conducted by using solar energy. SOMR was supplied by the local Aydın Olive Mill Company (3-phase), Akçay, Cyprus. The SOMR were dried at 105 °C for 8 h before solar torrefaction experiments. The particle size of used raw SOMR was in the range of 1 to 2 mm.

An old parabolic dish antenna was used for concentrating solar energy. Geometrical characteristics of parabolic dish are given in Table 1. The parabolic dish was covered with a reflective film in which the reflectivity is given as 1, from the producer company (Magic Plant, Turkey). The surface of the parabolic dish was completely covered by 10 triangular pieces of reflective film. Solar torrefaction was conducted in a cylindrical receiver-tube made of stainless steel. The receiver tube was fixed to focus the parabolic dish using copper wires. The receiver-tube had a circular-flat base with a diameter of 0.035 m and height of 0.1 m. The receiver-tube was painted black using a heat resistant paint (up to 300 °C) for increasing the amount of absorbed solar thermal energy.

Table 1. Geometrical Characteristics of the Parabolic Dish Concentrator

Diameter (d)	0.87 m
Focal Length (f)	0.59 m
($^{d}/_{f}$) Ratio	1.47
Rim Angle (Φ)	40.35°
Aperture Area (S)	0.59 m^2

The receiver tube was fed by nitrogen (20 mL/min) through the pipes as shown in Fig. 1 to provide an inert medium. Also, 50 mL/min nitrogen was allowed to flow for 10 min to remove oxygen in the receiver-tube before each solar torrefaction process.

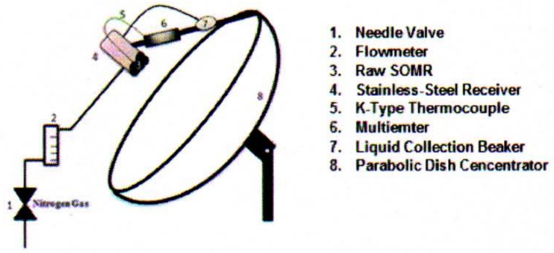

Fig. 1. Schematic representation of parabolic dish solar torrefier

Commented [MH1]: Please correct two items in the text within Fig. 1. Item number "6" has a spelling error. It should be "multimeter" Item 8 should have the word "Concentrator".

Gas produced during torrefaction process was taken outside from stainless steel and plastic pipes. Stainless steel pipes were connected to plastic pipes, which were covered with aluminum foil to prevent their melting. The solar torrefaction process was conducted at 250 °C. The holding time was adjusted to 10 min, which did not include the heating time. The maximum heating rate recorded for stainless steel reactor was 50 °C/min and reached the torrefaction temperature in 5 to 10 minutes. Solar torrefaction experiments were conducted on October 8, 2014 to October 10, 2014 between 11:30 am and 12:30 pm. The solar torrefaction experiments were repeated three times. Each experiment was conducted with 5 g of SOMR. The ultimate and proximate analysis results of solar torrefaction products are represented as average of each product. None of the results deviated more than 3.36% from the average. The analysis results of solar torrefaction products is represented by sSOMR in Figs. 2 to 5.

The elemental composition of solar torrefaction products was obtained from ultimate analysis. The Thermo Finnegan Flash EA 1112 Series Element Analyzer (Monza, Italy) were used to measure carbon (C), hydrogen (H), and nitrogen (N) in wt.%. Oxygen (O) was determined from the difference on dry basis (db) according to:

$$O(wt\%) = 100 - (C(wt\%) + H(wt\%) + N(wt\%) + S(wt\%) + Ash(wt\%)) \quad (1)$$

Volatile matter (VM), fixed carbon (FC), and ash content composition of the torrefaction products were determined by proximate analysis in wt%. The proximate analysis was carried out in a muffle furnace. sSOMR samples were dried at 105°C until their mass reach to a stable point before proximate analysis. Volatile matter content of moisture free sSOMR and SOMR samples was measured by heating in a moisture free covered crucible up to 950°C and kept at that temperature for 6 minutes. Volatile matter (VM) content of samples was determined according to Eq. 2.

$$\mathrm{VM} = 100 \times \frac{M_{\mathrm{sSOMR}} - M_{\mathrm{vm}}}{M_{\mathrm{sSOMR}}} \quad (2)$$

where, m_{sSOMR} is the mass of moisture free sSOMR before heating up to 950°C and m_{vm} is the mass of remaining sSOMR after heating up to 950°C and keeping at that temperature for 6 minutes. Ash content was measured after determination of volatile matter content. Volatile and moisture free sSOMR samples were heated up to 750°C and held at that temperature for 6 hours in an open crucible. Ash content was calculated according to Eq. 3.

$$Ash = 100 \times \frac{M_{ash}}{\mathrm{M_{sSOMR}}} \tag{3}$$

where, m_{ash} is the remained mass after heating up to 950 °C and keeping at that temperature for 6 hours. Fixed carbon (FC) content of produced sSOMR was determined according to Eq. 4.

$$FC\% = 100 - VM\% - Ash\,\% \tag{4}$$

The higher heating value (HHV) of sSOMR and SOMR were calculated by considering the carbon (C), hydrogen (H), nitrogen (N) and oxygen (O) content of the samples, according to Demirbaş *et al.* (1997), Eq. 5.

$$HHV(\tfrac{MJ}{kg}) = 0.335\,C(\mathrm{wt.\%}) + 1.42H(\mathrm{wt.\%}) - 0.154\,O(\mathrm{wt.\%}) - 0.145\,N(\mathrm{wt.\%}) \tag{5}$$

The mass yield and energy yield of solar torrefaction products were calculated according to the following equations:

$$Mass\ Yield\ (\%) = \frac{Mass\ of\ sSOMR}{Mass\ of\ Raw\ SOMR} \times 100 \tag{6}$$

$$Energy\ Yield\ (\%) = Mass\ Yield \times \frac{(HHV)_{sSOMR}}{(HHV)_{Raw\ SOMR}} \times 100 \tag{7}$$

RESULTS AND DISCUSSION

Appearance of Solar Torrefaction Products and Mass Yield

The appearance of raw SOMR and three solar torrefied SOMR are given in Fig. 2. The color of SOMR became darker after solar torrefaction.

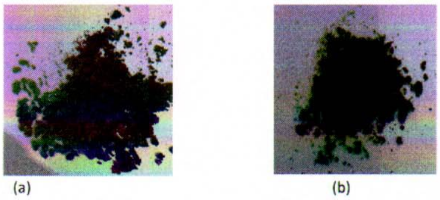
(a) (b)

Fig. 2. (a) Appearance of raw SOMR and (b) sSOMR produced by solar torrefier

The mass yield of sSOMR was 57.74% in dry basis. Isothermal (Chen and Kuo 2011a) and non-isothermal (Chen and Kuo 2011b) torrefaction studies were conducted with biomass constituents: cellulose, hemicellulose, lignin, and xylan. These studies revealed that hemicellulose and xylan were thermally degraded to form volatile products, such as H_2O, CO, CO_2, H, acetic acid, and other organics (Prins *et al.* 2006b), at a torrefaction temperature of 250°C. In this study, the mass loss during solar torrefaction was attributed to the degradation of hemicellulose (mainly xylan) and also to the removal of bound water.

Carbon (C), Hydrogen (H), Nitrogen (N), and Oxygen (O) Content of Solar Torrefied SOMR

The elemental composition of solar torrefied SOMR is demonstrated in Fig. 3. The carbon content of raw SOMR increased by an average of 7.65% after solar torrefaction. The hydrogen content of solar torrefied samples was reduced similar to torrefaction process. The amount of change in the hydrogen content of solar torrefied SOMR was around 0.41%. Also, sSOMR had lower oxygen. The change in oxygen content was 15.01%.

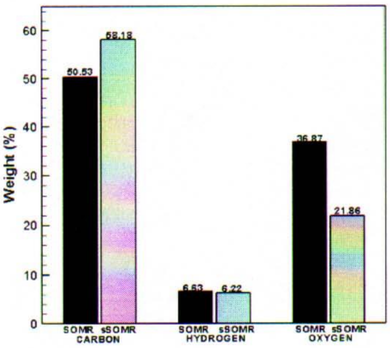

Fig. 3. Elemental composition of SOMR and sSOMR

Torrefaction is associated with the destroyed hydroxyl groups (–OH) (Bergman *et al.* 2005; Phanphanich and Mani 2011), which results in a solid fuel with reduced hydrogen and oxygen contents. Ultimate analysis of solar torrefied SOMR confirmed these results.

The H/C and O/C atomic ratios of sSOMR were calculated. The H/C ratio is an indicator of pyrolysis efficiency, where the O/C ratio is a measure of degree of oxidation (Schmidt *et al.* 2001; Nguyen *et al.* 2004). A reduced O/C ratio is a potential indicator of both hydrophilicity and polarity. Reduced polar surface groups results in a reduction of affinity of the fuel with water molecules (Manya 2012).

Figure 4 shows the O/C atomic ratios of raw SOMR and sSOMR. The average O/C ratio of sSOMR was almost half of O/C ratio of SOMR. Also, Fig. 4 shows the H/C atomic ratio of raw SOMR and sSOMR samples. The average H/C ratio of solar torrefaction products was 1.26, and the H/C ratio of SOMR was 1.56.

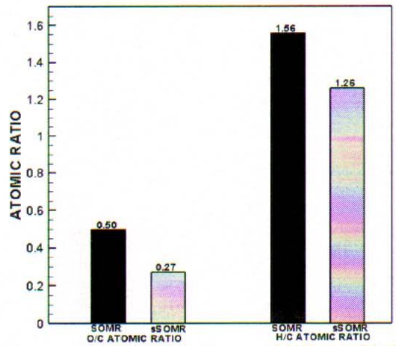

Fig. 4. O/C atomic ratio and H/C ratio of SOMR and sSOMR.

Volatile Matter (VM), Fixed Carbon (FC), and Ash Content of Raw and Solar Torrefied SOMR

The volatile matter and fixed carbon composition of solar torrefied SOMR was obtained by proximate analysis. Torrefaction studies done for various biomass studies and SOMR showed that torrefaction produces a solid fuel with reduced volatile matter and increased ash and fixed carbon content (Cellatoğlu and İlkan 2015, Chiou *et al.* 2015). Figure 5 shows the volatile matter content of raw SOMR and sSOMR. The volatile matter content of samples decreased by 14.84% after solar torrefaction. Reduced volatile matter is an indicator of more qualified fuel with less smoke during combustion (Patel and Gami 2012).

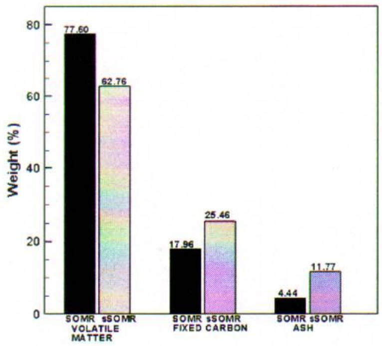

Fig. 5. Volatile matter, fixed carbon and ash content of SOMR and sSOMR

The fixed carbon content of solar torrefaction products is also given in Fig. 5. The average rate of change in carbon content of sSOMR was 7.50 wt.%. Figure 5 also shows that, solar torrefaction yielded higher ash content fuel and sSOMR contains 7.33% more ash compared to SOMR.

Higher Heating Value and Energy Yield of Solar Torrefied SOMR

Torrefaction studies conducted with different biomass have shown that torrefaction yields a solid fuel with higher HHV (Bridgeman *et al.* 2008). The HHV sSOMR is 22.85 MJ/kg, where HHV of SOMR is 19.76 MJ/kg on dry basis. Solar torrefaction yielded a solid fuel with 15.30% higher HHV than raw SOMR. Also, the energy yield calculations of solar torrefaction products showed that 67.25% of the original energy content was retained in products after solar torrefaction (on dry basis).

Thermal Performance of Parabolic Dish Solar Torrefier and Solar Torrefaction

The performance of a parabolic dish solar torrefier is measured by calculating its thermal efficiency. The thermal efficiency of a parabolic dish solar torrefier is defined as the ratio of the useful thermal energy transferred to the receiver to the energy incident on the parabolic dish collector aperture. The thermal efficiency (η) of the parabolic dish torrefier was calculated as follows,

$$\eta = {Q_{\mathrm{useful}}}/{Q_{\mathrm{aperature}}} \tag{8}$$

where the Q_{useful} is the amount of solar thermal energy that is transferred to the stainless steel receiver and $Q_{\mathrm{aperature}}$ is the energy incident on the parabolic dish collector.

$$Q_{\mathrm{useful}} = \dot{m}c(T - T_{\mathrm{O}}) \tag{9}$$

$$Q_{\mathrm{aperature}} = \alpha\, I_{\mathrm{B}}S \tag{10}$$

Table 2. Thermal Characteristics of the Parabolic Dish Torrefier

$\dot{m}$	0.00063 (kg/s)
c	510 (J/kg K)*
T	250 °C
T_{O}	24 °C
α	1
I_{B}	508 (W/m^2)**

*Average of maximum (530 J/kg K) and minimum (490 J/kg K) specific heat capacities associated with stainless steel.

** Average direct beam radiation in Northern Cyprus during October (Northern Cyprus Ministry of Public Tourism and Environment, Meteorology Department)

In the foregoing expressions, $\dot{m}$ is the ratio of mass of stainless steel receiver to heating time, c is the specific heat capacity of stainless steel, T is the torrefaction temperature, T_{O} is the ambient temperature, α is the reflectivity parabolic dish, I_{B} is the beam radiation on parabolic dish collector, and S is the aperature area of parabolic dish collector. In this study, the mass of the stainless steel receiver was 0.380 kg, and the mass of SOMR in each run was 0.005 kg.

The mass of SOMR used for solar torrefaction was neglected for thermal efficiency calculations. The thermal characteristics of the parabolic dish torrefier, used for efficiency calculation, are given in Table 2. The thermal efficiency calculations showed that the parabolic dish solar torrefaction system worked with 24.22% thermal efficiency.

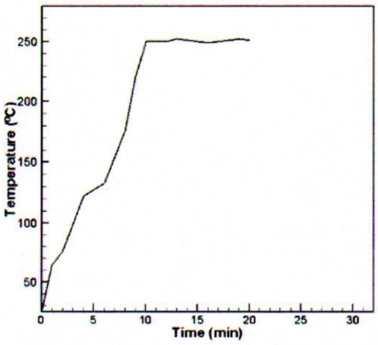

Fig. 6. Temperature profile of parabolic dish solar torrefier recorded on October 09 2014

Besides the thermal efficiency, the temperature profile of stainless steel receiver during solar torrefaction process is given in Fig. 6. The figure clearly shows that the intermittent structure of solar energy resulted in a non-uniform heating rate. Furthermore; after reaching temperature of 133ºC, the receiver experienced an almost constant heating rate. The non-uniformity in heating rate, during solar torrefaction, occurred in the first stage of torrefaction process. The first stage of torrefaction, namely drying, occurs at temperatures below 150ºC (Brachi *et al.* 2015). Temperatures above 150ºC are associated with removal of bounded water (Bhaskar and Pandey, 2015) and decomposition of hemicellulose (Brachi *et al.* 2015). In this study, since non-uniformity in heating rate occurred at temperatures below 150ºC, it did not result in any change torrefaction characteristics of solar torrefaction products.

Torrefaction of SOMR has been investigated by different researchers. Brachi *et al.* (2015) investigated the isoconversional kinetic analysis of olive pomace decomposition under torrefaction operating conditions. The authors showed that torrefaction of SOMR(or olive pomace) can be described by a single step model. Also, Chiou *et al.* (2015), Cellatoğlu and İlkan (2015), and Benavente and Fullana (2015) investigated the changes in elemental and proximate compositions of SOMR under different torrefaction conditions (temperature and holding time). Results of the cited studies showed that torrefaction yielded solid fuel with higher carbon, ash, and fixed carbon content and less oxygen, hydrogen and volatile matter content compared to raw SOMR. Cellatoğlu and İlkan (2015) showed that rising torrefaction temperature from 210ºC to 240ºC results in a significant change in elemental composition of SOMR. Furthermore, Chiou *et al.* (2015) showed that significant change in elemental composition occurs when temperature is raised from 230ºC to 260ºC. Consistent with studies of Chiou *et al.* (2015) and Cellatoğlu and İlkan (2015), solar torrefaction, conducted at 250°C, results in significant changes in elemental and proximate composition of SOMR. The torrefaction temperature of 250°C is also important because of the likely exothermic nature of the torrefaction process. Although, there is no consensus on the endothermic and exothermic nature of biomass torrefaction, many researchers have shown that exothermicity starts at torrefaction temperatures above 250°C (Cavagnol *et al.* 2015; Brachi *et al.* 2016).

This study showed that the torrefaction process can be conducted by using solar energy. The type of input energy did not affect the properties of products. The products have similar properties (higher HHV, higher carbon content, less oxygen content) in comparison with conventional torrefaction.

CONCLUSIONS

1. Solar torrefaction was tested experimentally by constructing a parabolic dish solar torrefier. Experimental results showed that the parabolic dish solar torrefier had a thermal efficiency of 24.22%.
2. The elemental composition and volatile matter, ash, and fixed carbon content of solar torrefaction products were investigated.
3. Ultimate and proximate analysis results indicated that conducting the torrefaction experiment with solar thermal energy did not change the torrefaction behavior of SOMR.
4. Solar thermal energy can be used as input energy for torrefaction. Furthermore, solar energy can be converted into a storable and transportable fuel.
5. Solar torrefied SOMR can be directly used as fuel. Also, it can be used for producing more qualified bio-oil, syngas, or charcoal *via* fast pyrolysis, gasification, or carbonization, respectively.

REFERENCES CITED

Bergman, P. C. A., and Kiel, J. H. A. (2005). "Torrefaction for biomass upgrading," 14th European Biomass Conference & Exhibition, Paris, France.

Benavente, V., and Fullana, A. (2015). "Torrefaction of olive mill waste," *Biomass and Bioenergy* 73, 186-194.

Brachi, P., Miccio, F., Miccio, M., and Ruoppolo, G. (2015). "Isoconversional kinetic analysis of olive pomace decomposition under torrefaction operating conditions," *Fuel Processing Technology* 130, 147-154.

Brachi, P., Miccio, F., Miccio, M., and Ruoppolo, G. (2016). "Torrefaction of tomato peel residues in a fluidized bed of inert particles and a fixed-bed reactor," *Energy Fuels* 30(6), 4858-4868. DOI: 10.1021/acs.energyfuels.6b00328

Bhaskar, T., and Pandey, A. (2015). "Advances in thermochemical conversion of biomass," in: *Recent Advances in Thermochemical Conversion of Biomass*, A. Pandey (ed.), Elsevier B.V., pp. 3-30.

Bridgeman, T. G., Jones, J. M., Shield, I., and Williams, P. T. (2008). "Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties," *Fuel* 87(6), 844-856. DOI: 10.1016/j.fuel.2007.05.041

Cavagnol, S., Roesler, J. F., Sanz, E., Nastoll, W., Lu, P., and Perré, P. (2015). "Exothermicity in wood torrefaction and its impact on product mass yields: From micro to pilot scale," *The Canadian Journal Of Chemical Engineering* 93, 331-339. DOI: 10.1002/cjce.22128

Cellatoğlu, N., and İlkan, M. (2015). "Torrefaction of solid olive mill residue," *BioResources* 10(3), 5876-5889. DOI: 10.15376/biores.10.3.5876-5889

Cellatoğlu, N., and İlkan, M. (2016). "Effects of torrefaction on carbonization characteristics of solid olive mill residue," *BioResources* 11(3), 6286-6298.

Chen, W.-H., and Kuo, P.-C. (2011a). "Isothermal torrefaction kinetics of hemicellulose, cellulose, lignin and xylan using thermogravimetric analysis," *Energy* 36, 64-51. DOI: 10.1016/j.energy.2011.09.022

Chen, W.-H., and Kuo, P.-C. (2011b). "Torrefaction and co-torrefaction characterization of hemicellulose, cellulose and lignin as well as torrefaction of some basic constituents in biomass," *Energy* 36(2), 803-811. DOI: 10.1016/j.energy.2010.12.036

Chiou, B.-S., Medina, D. V., Bilbao-Sainz, C., Klamczynski, A. K., Avena-Bustillos, R. J., Milczarek, R. R., Du, W.-X., Glenn, G. M., and Orts, W. J. (2015). "Torrefaction of pomaces and nut shells," *Bioresource Technology* 177, 58-65.

Couhert, C., Salvador, S., and Commandre, J. M. (2009). "Impact of torrefaction on syngas production from wood," *Fuel* 88(11), 2286-2290. DOI:10.1016/j.fuel.2009.05.003

Demirbaş, A., Güllü, D., Çaglar, A., and Akdeniz, F. (1997). "Estimation of calorific values of fuels from lignocellulosics," *Energy Sources* 19(8), 765-770. DOI: 10.1080/00908319708908888

Deng, J., Wang G. J., Kuang, J. H., Zhang, Y. L., and Luo, Y. H. (2009). "Pretreatment of agricultural residues for co-gasification via torrefaction," *J. Anal. Appl. Pyrolysis* 86(2), 331-337. DOI: 10.1016/j.jaap.2009.08.006

Dermechea, S., Nadour, M, Larroche, C., Moulti-Mati, F., and Michaud, P. (2013). "Olive mill wastes: Biochemical characterizations and valorization strategies," *Process Biochemistry* 48, 1532-1552. DOI: 10.1016/j.procbio.2013.07.010

Deutmeyer, M., Bradley, D., Hektor, B., Hess, R., Tumuluru, J., Nikolaisen, L., and Wild, M. (2012). *Possible Effect of Torrefaction on Biomass Trade*, IEA Bioenergy, Paris, France.

Doymaz, I., Gorel, O., and Akgün, D. (2004). "Drying characteristics of the solid by-product of olive oil extraction," *Biosystems Engineering* 88(2), 213-219. DOI: 10.1016/j.biosystemseng.2004.03.003

Felfri, F. F., Luengo, C. A., Suarez, J. A., and Beaton, P. A. (2005). "Wood briquette torrefaction," *Energy for Sustainable Development* 9(3), 19-22. DOI: 10.1016/S0973-0826(08)60519-0

Gomez-Munoz, B., Hatch, J. D., Bol, R., and Garcia-Ruiz, R. (2012). "The compost of olive mill pomace: From a waste to a resource – Environmental benefits of its application in olive oil groves," in: *Sustainable Development - Authoritative and Leading Edge Content for Environmental Management*, S. Curkovic (ed.), InTech, Rijeka, Croatia, pp. 459-484. DOI: 10.5772/48244

Manya, J. J. (2012). "Pyrolysis for biochar purposes: A review to establish current knowledge gaps and research needs," *Environ. Sci. Technol.* 46(15), 7939-7954. DOI: 10.1021/es301029g

Nguyen, T. H., Brown, R. A., and Ball, W. P. (2004). "An evaluation of thermal resistance as a measure of black carbon content in diesel soot, wood char, and sediment," *Org. Geochem.* 35, 217-234. DOI: 10.1016/j.orggeochem.2003.09.005

Northern Cyprus Ministry of Public Tourism and Environment (2016). "Meteorology department," (http://www.kktcmeteor.org//meteorolojikbilgi/kibris-iklimi.aspx), Accessed on July 11, 2016.

Patel, B., and Gami, B. (2012). "Biomass characterization and its use as solid fuel for combustion," *Iranica J. Energy Environ.* (IJEE) 3(2), 123-128. DOI: 10.5829/idosi.ijee.2012.03.02.0071

Phanphanich, M., and Mani, S. (2011). "Impact of torrefaction on the grindability and fuel characteristics of forest biomass," *Bioresource Technol.* 102, 1246-1253. DOI: 10.1016/j.biortech.2010.08.028

Prins, J. M., Ptasinski, J. K., and Janssen, J. J. G. F. (2006a). "Torrefaction of wood Part 1. Weight kinetics," *J. Anal. Appl. Pyrolysis* 77, 28-34. DOI: 10.1016/j.jaap.2006.01.002

Prins, M. J., Ptasinski, J. K., and Frans J. J. G. F. (2006b). "More efficient biomass gasification *via* torrefaction," *Energy* 31, 3458-3470. DOI: 10.1016/j.energy.2006.03.008

REN 21 (2014). *Renewables 2014 Global Status Report*, Paris, France.

Sadaka, S., and Negi, S. (2009). "Improvements of biomass physical and thermochemical characteristics *via* torrefaction process," *Environ. Prog. Sustain. Energy* 28, 427-434. DOI: 10.1002/ep.10392

Sadeghi, H., Akbarpour, V., and Movaghatnezhad, K. (2010). "Investigation of olive stones as lignocellulose material for bioethanol production," *American –Eurasian J. Agric. & Environ. Sci.* 8(5), 520-524.

Sarkar, M., Kumar, A., Tumuluru, J. S., Patil, K. N., and Bellmer, D. D. (2014). "Gasification performance of switchgrass pretreated with torrefaction and densification," *Appl. Energy* 127, 194-201. DOI: 10.1016/j.apenergy.2014.04.027

Schmidt, M. W. I., Skjemstad, J. O., Czimczik, C. I., Glaser, B. Prentice, K. M., Gelinas, Y., and Kuhlbusch, T. A. J. (2001). "Comparative analysis of black carbon in soils," *Global Biogeochem. Cycles* 15, 163-167. DOI: 10.1029/2000GB001284

Sesli, M., and Yeğenoğlu, E. D. (2009). "RAPD-PCR analysis of cultured type olives in Turkey," *African J. Biotechnol.* 8, 3418-3423.

Rousset, P., Aguiar, C., Labbe, N., and Commandre, J.-M. (2011). "Enhancing the combustible properties of bamboo by torrefaction," *Bioresource Technol.* 102, 8225-8231. DOI: 10.1016/j.biortech.2011.05.093

Yan, W., Acharjee, T. C., Coronella, C. J., and Vasquez, V. R. (2009). "Thermal pretreatment of lignocellulosic biomass," *Environ. Prog. Sustainable Energy* 28(3), 435-440.

Zheng, A., Zhao, Z., Sheng, C., Huang, Z., Wang, X., He, F., and Li, H. (2013). "Effect of torrefaction on structure and fast pyrolysis behavior of corncobs," *Bioresource Technol.* 128, 370-377. DOI: 10.1016/j.biortech.2012.10.067

Article submitted: June 17, 2016; Peer review completed: August 7, 2016; Revised version received and accepted: Sept. 1, 2016; Published: