

Study of Biomass Torrefaction Fundamentals and Properties

Singh, Jaswinder

Chitkara College of Applied Engineering, Chitkara University

Srivastava, Prateek

Chitkara University Institute of Engineering and Technology, Chitkara University

Goyal, Deepam

Chitkara University Institute of Engineering and Technology, Chitkara University

<https://doi.org/10.5109/6781092>

出版情報 : Evergreen. 10 (1), pp.348-355, 2023-03. 九州大学グリーンテクノロジー研究教育センター
バージョン :

権利関係 : Creative Commons Attribution-NonCommercial 4.0 International



Study of Biomass Torrefaction Fundamentals and Properties

Jaswinder Singh¹, Prateek Srivastava^{2,*}, Deepam Goyal²

¹Chitkara College of Applied Engineering, Chitkara University, Punjab

²Chitkara University Institute of Engineering and Technology, Chitkara University, Punjab

*Author to whom correspondence should be addressed:

E-mail: prateek.srivastava@chitkara.edu.in

(Received July 12, 2022; Revised January 24, 2023; accepted January 24, 2023).

Abstract: The heating value of coal is necessary for its usage in power generating. This is tested experimentally, although theoretical models have been used to forecast the heating value; either lower heating value or greater heating value. The same approach has been used to biomass, which is being promoted as an alternative for coal or as a co-fired fuel. Biofuel production was seen as a significant countermeasure for lowering anthropogenic CO₂ emissions, removing the worsening greenhouse effect in the atmosphere, and slowing global warming. Thermochemical conversion is thought to be the most effective method of generating biofuels from biomass, with the least potential for global warming. The torrefied biomass is used for making biomass material into a useful energy and it also enhance the property of that material by torrefied it.

Keywords: Torrefaction, biomass, biofuels

1. Introduction

Torrefaction of biomass has gained widespread attention. For instance, it can be used to replace coal in the production of steel or to work with coal in a precise ratio of co-firing with biomass to reduce emissions¹⁻³. Biomass torrefaction has been the subject of numerous articles, but this study attempts to approach it from a different perspective by highlighting different torrefaction components and how they relate to other technologies, as well as by illuminating the chemistry that underlies its operations and byproducts⁴⁻⁶. It is safe to say that a lot has changed with the technologies utilized in the process. There is a change in attention to raw biomass and how it is analysed, along with the different analyses conducted to derive useful information about the biomass characteristics^{7,8}. Different types of reactors are in use, but there is no favoured one because they all have pros and cons^{9,10}. There are no substantial variations between them, thus it's the procedure that's the focus, rather than the reactor itself^{11,12}. The main output of the process determines its efficiency and how it might be used with other technologies. Current biomass torrefaction methods include co-firing with coal, as well as pre-treatment for pyrolysis and gasification¹³⁻¹⁵. The technique has not yet achieved its full potential because to the varied forms of biomass in different nations, but it is believed that it will with the growing need for renewable energy sources¹⁶⁻¹⁸. The preliminary dye application is imperative the advanced it is, the worse the removal value^{19,20}.

2. Biomass

Plants and animals that are alive or have been dead for a brief length of time might be considered biomass^{21,22}. By converting atmospheric carbon dioxide into carbohydrates, plants produce biomass²³⁻²⁵. In the process of eating these botanical or other biological species, biota will multiply and contribute to the biomass chain to convert CO₂ into glucose and release O₂ as a waste product, green plants break down water in the presence of visible light, particularly in the blue (425–450 nm) or red (600–700 nm) wavelength ranges. This process is called photosynthesis²⁶⁻²⁸.

2.1 Conversion of biomass

The biomass basically divides into three types of products as show in in Fig. 1.

2.2 Gaseous products

Gasification, a thermochemical process that exposes biomass to high temperatures and little oxygen, can be used to turn biomass into gaseous compounds²⁹⁻³¹.

As a first step, the biomass char (C) is burnt in order to create CO₂, CO gases, and HO. As a result, gasification reactions take place in line with the reactions that have taken place³²⁻³⁵.

2.3 Liquid products

There are several methods that may be used to turn biomass into liquid products like biodiesel or bio-oil^{33,36}.

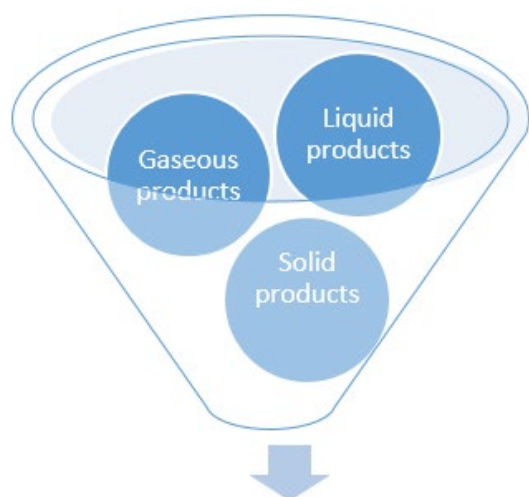


Fig. 1: Conversion of biomass

biomass into liquid products like biodiesel or bio-oil^{37,38}). In the processes described below, pyrolysis generates charcoal, bio-oil, methanol, and gases from wood or coal^{39,40}). A common mixture of gases generated by pyrolysis is a mixture of CO₂, H₂O, CO, and CH₄. Water, tar, and moisture combine to form bio-oil (tar is a mixture of complex hydrocarbons)⁴¹). This process happens between 300 and 7000 °C, although it may also occur between 200 and 1000 °C.

2.4 Solid products

Fuels like coal may be made from biomass through carbonization and torrefaction, and then burnt directly to create heat and electricity^{42–44}). As well as liquid products, there are also gaseous products, which may be classified into permanent and condensable. Permanent gases include CO₂, CO, and so on, while condensable gases include H₂O, acetic acid, and so on^{45,46}). Thermal decomposition takes place at temperatures ranging from 200°C to 3000°C.

3. Torrefaction

Turfing was invented to enhance its characteristics so that they would equal coal's. s^{47–49}). It takes a lot of water to prepare coal for use in power production, and this valuable resource is becoming increasingly rare^{50–56}). Nonrenewable coal has been replaced by renewable resources to continue our industrial advantages⁵⁷). Coal is a nonrenewable resource. Observable verity causing the cells can soak up plenty carbon in favor of metabolism^{58,59}). The demand for electricity is rising as more and more nations promote renewable energy sources and switch to electric vehicles. The use of solar electricity, wind power and biogas for illumination is becoming more popular amongst some individuals. In energy generation and metallurgical uses, coal must be substituted. Alternatively, a torrefied biomass can be used in this situation. Coal on the other hand releases harmful gases when burnt.

3.1 Torrefaction analysis

Torrefaction typically requires raw biomass that has been dried and nitrogen gas to create an inert environment^{50,60}). However, it has been shown that biomass torrefaction in inert circumstances delivers the greatest results. In order to compare biomass to coal, it can be characterized⁶¹). There will be a discussion of the various analyses presently as shown in Fig. 2

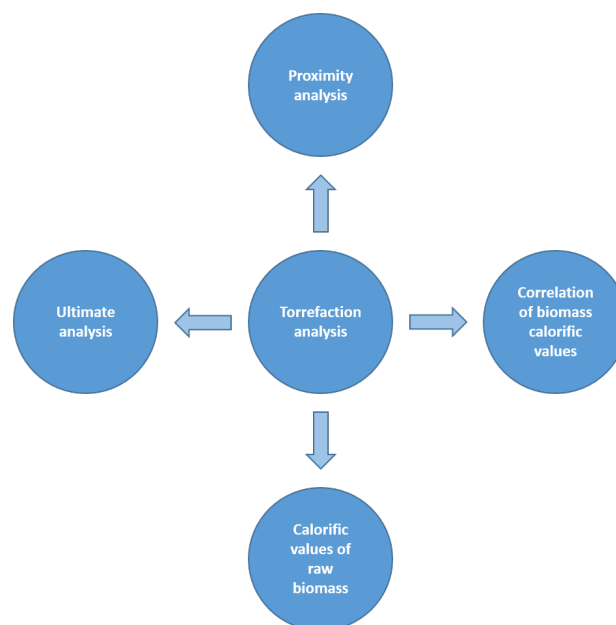


Fig. 2: Analysis of torrefaction

3.2 Proximity analysis

Wetness (MC), Ash, Volatile Matter, and Fixed Carbon are all measured using the standard test on a sample of biomass that has been dried and ground. These studies on coal have not been carried out for a very long time, and they provide a great basis for assessing how biomass, whether raw or torrefied, compares to coal in terms of energy output⁶²). This material was calculated using a variety of formulas, including

% MC = percentage of mild carbon

% ASH = mass of residue/ initial mass of sample X100

%VM = mass loss due to VM/initial dry mass of sample X 100

% FC = (%MC + % ASH + %VM)

3.3 Ultimate analysis

While biomass and coal contain mineral stuff as well, the major chemical components found in biomass and coal include carbon and hydrogen (O). Chemometric analysis is essential for estimating biomass material balance and calorific value. ASTM E870-82 (2013) is used for the final examination of wood fuel (ASTM, 2019d). Methods for calculating elements i.e. carbon, hydrogen, nitrogen and sulphur (CHNS) are described in this standard. There are several tests that may be performed in order to find out what the elemental condition of biomass.

3.4 Calorific value of raw biomass

A fuel's calorific value is the quantity of heat generated when a fuel (such as coal or biomass) is entirely burnt at the condition of combustion products⁶³. Typically, it is reported at two distinct temperatures, which are 25°C and 1000°C, respectively.

3.5 Correlations of biomass calorific value

It is possible to adapt the conventional coal testing procedures to biomass if analytical equipment is not readily available. Temperature values for biomasses can also be calculated using correlations built over time⁶⁴. A few assumptions found in the literature may be utilized to estimate the calorific value of coal using Dulong's equations⁶⁵.

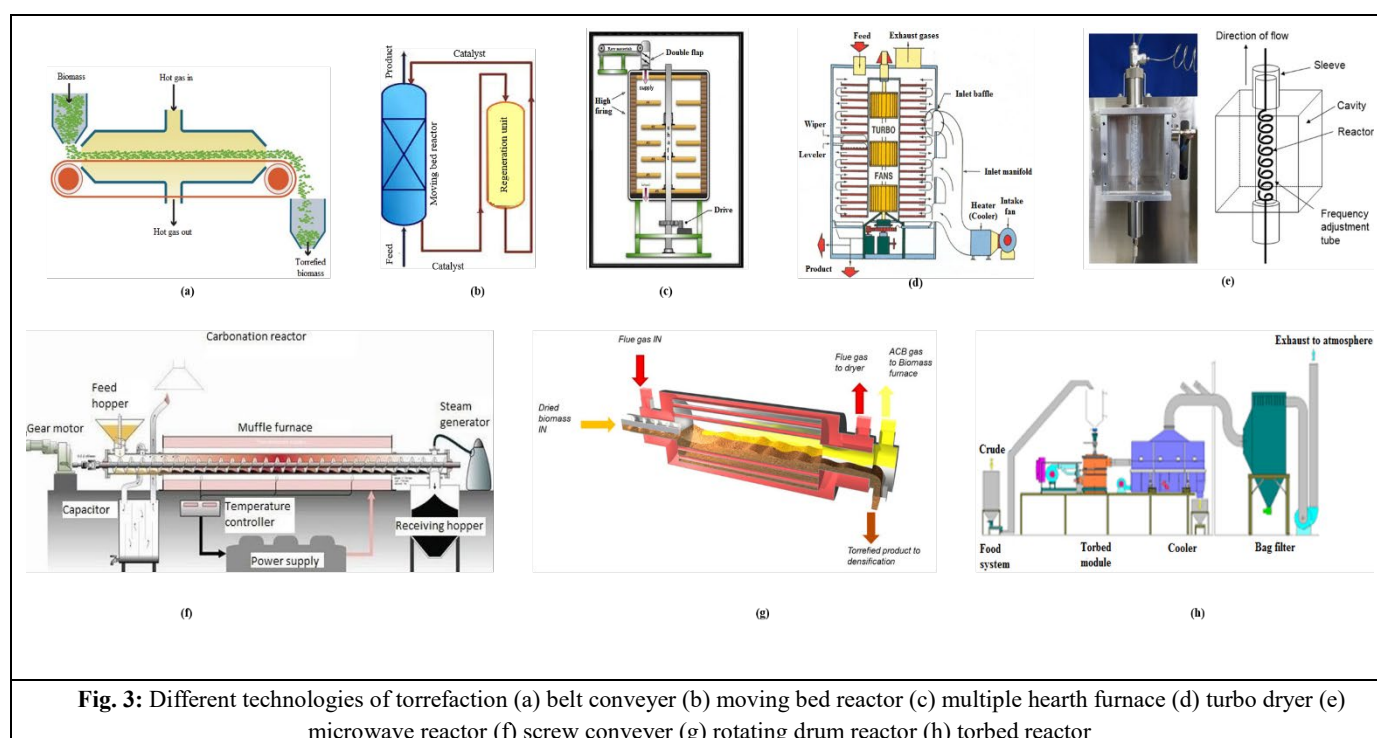
3.6 Technologies of torrefaction

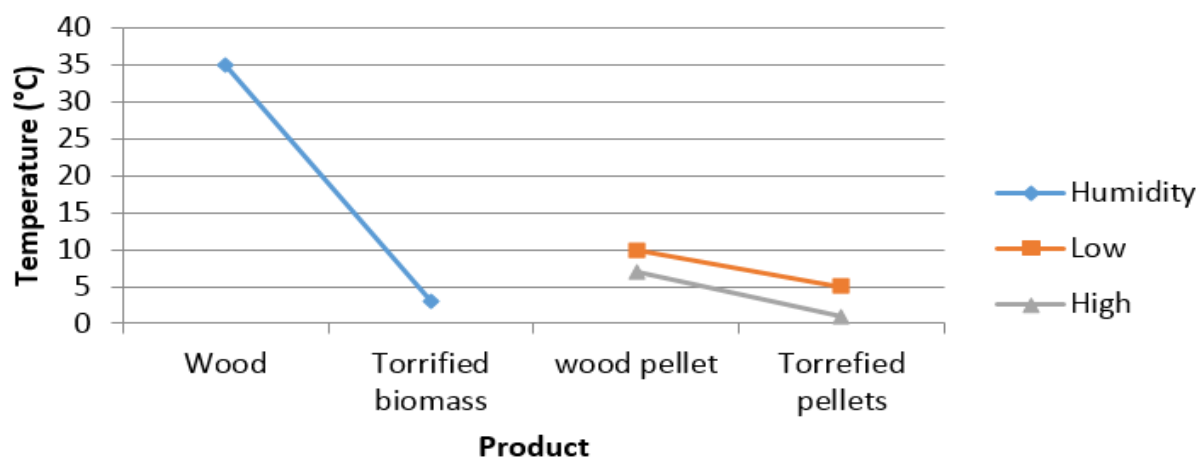
There are various types of technologies such as rotating drum reactor, Affecting bed reactor, Screw conveyor reactor, oscillating bed reactor, tarbed reactor, turbo dryer and micro reactor as shown in Fig. 3.

The business of producing heat and electricity from sustainable biomass sources is expanding, and as a result, the world market for biomass, particularly biomass pellets, has grown significantly pellets^{50,66}. Lingo cellulosic biomass is less homogeneous and has lower bulk and energy densities than traditional fuels. Torrefaction and other thermal pre-treatment methods are applied to enhance the fuel characteristics of biomass, i.e. lesser content of oxygen and water in the fuel, better storage and milling properties⁶⁷. “The process of torrefaction involves

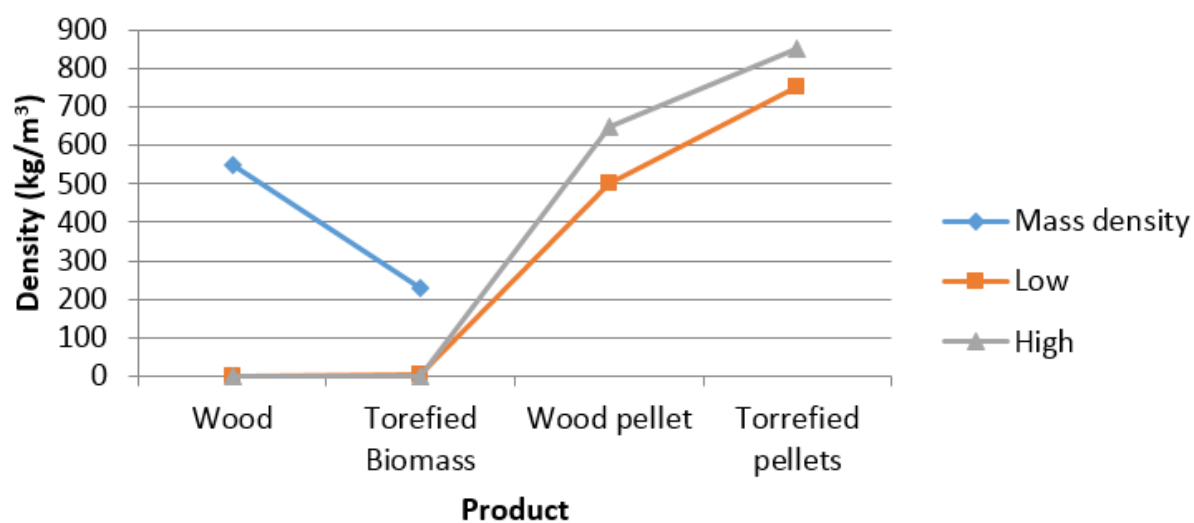
roasting biomass at temperatures between 240 and 320 °C in an atmosphere with little to no oxygen.

Torrefaction produces a product with low O/C and H/C atomic ratios by removing low molecular weight volatiles and moisture from biomass. Due to the heat breakdown of the biomass polymers, specifically hemicellulose, lignin, and cellulose, the mechanical properties of the fibres are changed after thermal treatment, causing the fibres to become brittle and partially hydrophobic. To enhance the handling characteristics of torrefied biomass, torrefaction is sometimes combined with palletization or briquetting processes.^{68–70} The method that produces the biofuels effectively is laptolyngbya^{71,72}. The objective is to produce a long-lasting, water-resistant energy carrier that can be employed in the existing storage and conveying amenities designed for hard coal, making them a superior replacement for coal in current heat and power plants⁷³. Torrefied biomass pellets are less expensive to transport store since they have a higher energy density per volume than conventional fuels biofuels like wood chips or pellets,⁷⁴. The bulk density of torrefied wood can range from 200-400 kg/m³ for torrefied wood chips to 600-850 kg/m³ for torrefied pellets, depending on the species and processing circumstances⁵².”A summary of the fuel's characteristics and a comparison to other solid biofuels are shown in Fig. 4⁷⁵

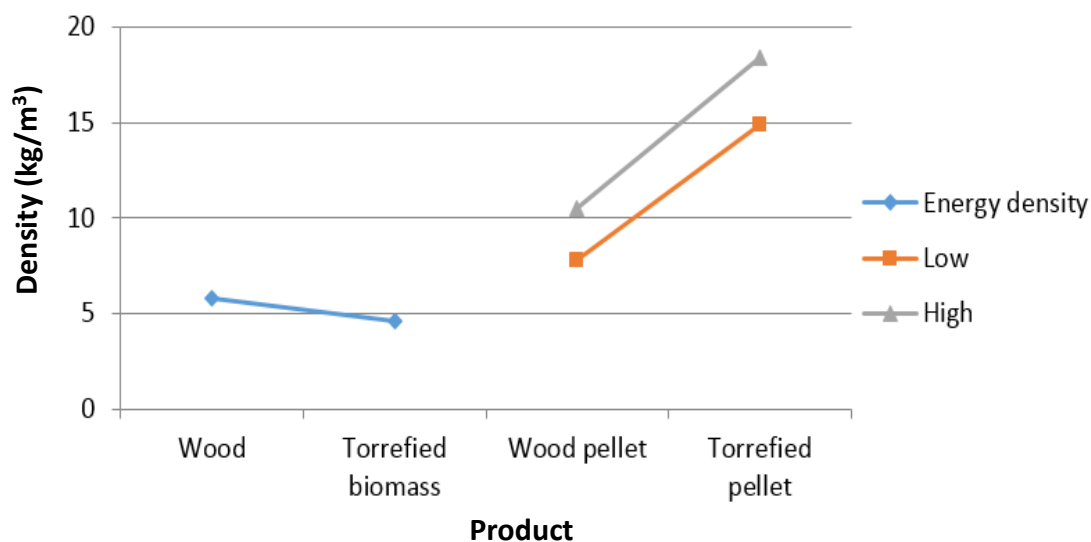




(a) Humidity



(b) Mass density



(c)

Energy density

Fig. 4: Variation of parameters for biomass torrefaction

Fig. 5 describes the process by which raw materials are transformed into torrefied materials at varying temperatures. After a while, the pellets grew darker and rougher as torrefaction temperature climbed, especially for pellets torrefied at 270°C. They found that changes in the acid-insoluble lignin component, rather than the carbohydrate portion, were responsible for the colour shift.

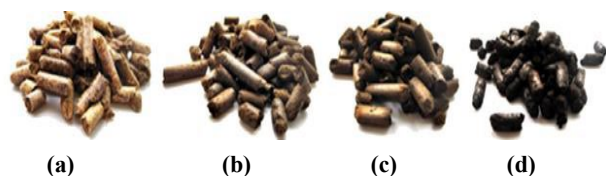


Fig. 5: Transformation of raw materials into torrefied materials (a) un-torrefied pallet (b) and (c) intermediate pallets (d) torrefied pallet

4. Conclusion

Torrefied biomass is gaining in popularity as a greener option than coal. Torrefier designs are patented by a variety of firms, each of whom claims supremacy over the others. Selection of a torrefaction technology has become extremely challenging due to the lack of a standard method for comparing different types of reactors. With this study, an essential knowledge gap in torrefaction technology is attempted to be filled by reviewing reactor types, comparing their torrefaction performance on an equal footing, and examining its economic consequences.

Ammonia emissions from urea fertilizer plants during the past few years, as well as their reduction, have become a serious issue. Continuous ammonia emissions cause human skin, eyes, mouth, and lungs to burn, drawing attention to accidental emissions brought on by sudden plant operating failure. The abrupt breakdown of a plant operation as a result of ineffective maintenance policy has a substantial impact on both human health and the profitability of the industry under consideration.

References

- 1) Y. Niu, Y. Lv, Y. Lei, S. Liu, Y. Liang, D. Wang, and S. Hui, "Biomass torrefaction: properties, applications, challenges, and economy," *Renew. Sustain. Energy Rev.*, **115** 109395 (2019). doi:10.1016/J.RSER.2019.109395.
- 2) M.J. Prins, K.J. Ptasiński, and F.J.J.G. Janssen, "Torrefaction of wood: part 2. analysis of products," *J. Anal. Appl. Pyrolysis*, **77** (1) 35–40 (2006). doi:10.1016/J.JAAP.2006.01.001.
- 3) B. Acharya, A. Dutta, and J. Minaret, "Review on comparative study of dry and wet torrefaction," *Sustain. Energy Technol. Assessments*, **12** 26–37 (2015). doi:10.1016/J.SETA.2015.08.003.
- 4) B. Arias, C. Pevida, J. Fiermoso, M.G. Plaza, F. Rubiera, and J.J. Pis, "Influence of torrefaction on the grindability and reactivity of woody biomass," *Fuel Process. Technol.*, **89** (2) 169–175 (2008). doi:10.1016/J.FUPROC.2007.09.002.
- 5) W.H. Chen, "Torrefaction," *Pretreat. Biomass Process. Technol.*, 173–192 (2015). doi:10.1016/B978-0-12-800080-9.00010-4.
- 6) R.L. Isemin, A. V. Mikhalev, N.S. Muratova, V.S. Kogh-Tatarenko, Y.S. Teplitskii, E.K. Buchilko, A.Z. Greben'kov, and E.A. Pitsukha, "Improving the efficiency of biowaste torrefaction," *Therm. Eng. 2019* 667, **66** (7) 521–526 (2019). doi:10.1134/S0040601519070048.
- 7) Y.L. Lin, N.Y. Zheng, and C.H. Hsu, "Torrefaction of fruit peel waste to produce environmentally friendly biofuel," *J. Clean. Prod.*, **284** 124676 (2021). doi:10.1016/J.JCLEPRO.2020.124676.
- 8) S. Negi, G. Jaswal, K. Dass, K. Mazumder, S. Elumalai, and J.K. Roy, "Torrefaction: a sustainable method for transforming of agri-wastes to high energy density solids (biocoal)," *Rev. Environ. Sci. Bio/Technology* 2020 192, **19** (2) 463–488 (2020). doi:10.1007/S11157-020-09532-2.
- 9) L.J.R. Nunes, and J.C.O. Matias, "Biomass torrefaction as a key driver for the sustainable development and decarbonization of energy production," *Sustain. 2020, Vol. 12, Page 922*, **12** (3) 922 (2020). doi:10.3390/SU12030922.
- 10) L. Wang, L. Riva, Ø. Skreiberg, R. Khalil, P. Bartocci, Q. Yang, H. Yang, X. Wang, D. Chen, M. Rudolfsson, and H.K. Nielsen, "Effect of torrefaction on properties of pellets produced from woody biomass," *Energy and Fuels*, **34** (12) 15343–15354 (2020). doi:10.1021/ACS.ENERGYFUELS.0C02671/ASSET/IMAGES/LARGE/EF0C02671_0011.JPEG.
- 11) J.J. Chew, and V. Doshi, "Recent advances in biomass pretreatment – torrefaction fundamentals and technology," *Renew. Sustain. Energy Rev.*, **15** (8) 4212–4222 (2011). doi:10.1016/J.RSER.2011.09.017.
- 12) M.N. Cahyanti, T.R.K.C. Doddapaneni, and T. Kikas, "Biomass torrefaction: an overview on process parameters, economic and environmental aspects and recent advancements," *Bioresour. Technol.*, **301** 122737 (2020). doi:10.1016/J.BIORTECH.2020.122737.
- 13) K.A. Abdulyekeen, A.A. Umar, M.F.A. Patah, and W.M.A.W. Daud, "Torrefaction of biomass: production of enhanced solid biofuel from municipal solid waste and other types of biomass," *Renew. Sustain. Energy Rev.*, **150** 111436 (2021). doi:10.1016/J.RSER.2021.111436.
- 14) Y. Furutani, K. Norinaga, S. Kudo, J.I. Hayashi, and T. Watanabe, "Current situation and future scope of biomass gasification in japan," *Evergreen*, **4** (4) 24–29 (2017). doi:10.5109/1929681.
- 15) A. Soria-Verdugo, E. Cano-Pleite, A. Panahi, and A.F. Ghoniem, "Kinetics mechanism of inert and oxidative torrefaction of biomass," *Energy Convers.*

- Manag., **267** 115892 (2022). doi:10.1016/J.ENCONMAN.2022.115892.
- 16) J.M.C. Ribeiro, R. Godina, J.C. de O. Matias, and L.J.R. Nunes, "Future perspectives of biomass torrefaction: review of the current state-of-the-art and research development," *Sustain.* **2018**, Vol. 10, Page 2323, **10** (7) 2323 (2018). doi:10.3390/SU10072323.
- 17) N.A. Lestari, "Reduction of co2 emission by integrated biomass gasific ation-solid oxide fuel cell combined with heat recovery and in-situ co2 utilization," *Evergreen*, **6** (3) 254–261 (2019). doi:10.5109/2349302.
- 18) W.H. Chen, R. Aniza, A.A. Arpia, H.J. Lo, A.T. Hoang, V. Goodarzi, and J. Gao, "A comparative analysis of biomass torrefaction severity index prediction from machine learning," *Appl. Energy*, **324** 119689 (2022). doi:10.1016/J.APENERGY.2022.119689.
- 19) R. Muhammad, and S. Adityosulindro, "Biosorption of brilliant green dye from synthetic wastewater by modified wild algae biomass," (2022).
- 20) M. Manouchehrinejad, E.M.T. Bilek, and S. Mani, "Techno-economic analysis of integrated torrefaction and pelletization systems to produce torrefied wood pellets," *Renew. Energy*, **178** 483–493 (2021). doi:10.1016/J.RENENE.2021.06.064.
- 21) J. Shao, W. Cheng, Y. Zhu, W. Yang, J. Fan, H. Liu, H. Yang, and H. Chen, "Effects of combined torrefaction and pelletization on particulate matter emission from biomass pellet combustion," *Energy & Fuels*, **33** (9) 8777–8785 (2019). doi:10.1021/ACS.ENERGYFUELS.9B01920.
- 22) S.K. Thengane, K.S. Kung, A. Gomez-Barea, and A.F. Ghoniem, "Advances in biomass torrefaction: parameters, models, reactors, applications, deployment, and market," *Prog. Energy Combust. Sci.*, **93** 101040 (2022). doi:10.1016/J.PECS.2022.101040.
- 23) Q. Wang, S. Sun, X. Zhang, H. Liu, B. Sun, and S. Guo, "Influence of air oxidative and non-oxidative torrefaction on the chemical properties of corn stalk," *Bioresour. Technol.*, **332** 125120 (2021). doi:10.1016/J.BIORTECH.2021.125120.
- 24) G.M. Joselin Herbert, and A. Unni Krishnan, "Quantifying environmental performance of biomass energy," *Renew. Sustain. Energy Rev.*, **59** 292–308 (2016). doi:10.1016/J.RSER.2015.12.254.
- 25) Z. Kwoczynski, and J. Čmelík, "Characterization of biomass wastes and its possibility of agriculture utilization due to biochar production by torrefaction process," *J. Clean. Prod.*, **280** 124302 (2021). doi:10.1016/J.JCLEPRO.2020.124302.
- 26) M.J. Prins, K.J. Ptasiński, and F.J.J.G. Janssen, "More efficient biomass gasification via torrefaction," *Energy*, **31** (15) 3458–3470 (2006). doi:10.1016/J.ENERGY.2006.03.008.
- 27) D. Chen, F. Chen, K. Cen, X. Cao, J. Zhang, and J. Zhou, "Upgrading rice husk via oxidative torrefaction: characterization of solid, liquid, gaseous products and a comparison with non-oxidative torrefaction," *Fuel*, **275** 117936 (2020). doi:10.1016/J.FUEL.2020.117936.
- 28) K.B. Kota, S. Shenbagaraj, P.K. Sharma, A.K. Sharma, P.K. Ghodke, and W.H. Chen, "Biomass torrefaction: an overview of process and technology assessment based on global readiness level," *Fuel*, **324** 124663 (2022). doi:10.1016/J.FUEL.2022.124663.
- 29) I. Abdullah, N. Ahmad, M. Hussain, A. Ahmed, U. Ahmed, and Y.K. Park, "Conversion of biomass blends (walnut shell and pearl millet) for the production of solid biofuel via torrefaction under different conditions," *Chemosphere*, **295** 133894 (2022). doi:10.1016/J.CHEMOSPHERE.2022.133894.
- 30) E.A. Silveira, S. Luz, K. Candelier, L.A. Macedo, and P. Rousset, "An assessment of biomass torrefaction severity indexes," *Fuel*, **288** 119631 (2021). doi:10.1016/J.FUEL.2020.119631.
- 31) H. Lu, Y. Gong, C. Areeprasert, L. Ding, Q. Guo, W.H. Chen, and G. Yu, "Integration of biomass torrefaction and gasification based on biomass classification: a review," *Energy Technol.*, **9** (5) 2001108 (2021). doi:10.1002/ENTE.202001108.
- 32) H. Mikulčić, J. Baleta, and J.J. Klemeš, "Sustainability through combined development of energy, water and environment systems," *J. Clean. Prod.*, **251** 119727 (2020). doi:10.1016/J.JCLEPRO.2019.119727.
- 33) W. Yi, D. Zheng, X. Wang, Y. Chen, J. Hu, H. Yang, J. Shao, S. Zhang, and H. Chen, "Biomass hydrothermal conversion under co2 atmosphere: a way to improve the regulation of hydrothermal products," *Sci. Total Environ.*, **807** 150900 (2022). doi:10.1016/J.SCITOTENV.2021.150900.
- 34) F. Güleç, O. Williams, E.T. Kostas, A. Samson, and E. Lester, "A comprehensive comparative study on the energy application of chars produced from different biomass feedstocks via hydrothermal conversion, pyrolysis, and torrefaction," *Energy Convers. Manag.*, **270** 116260 (2022). doi:10.1016/J.ENCONMAN.2022.116260.
- 35) Y. Sun, S. Tong, X. Li, F. Wang, Z. Hu, O.D. Dacres, E.M.A. Edreis, N. Worasuwannarak, M. Sun, H. Liu, H. Hu, G. Luo, and H. Yao, "Gas-pressurized torrefaction of biomass wastes: the optimization of pressurization condition and the pyrolysis of torrefied biomass," *Bioresour. Technol.*, **319** 124216 (2021). doi:10.1016/J.BIORTECH.2020.124216.
- 36) L. Dai, Y. Wang, Y. Liu, R. Ruan, C. He, Z. Yu, L. Jiang, Z. Zeng, and X. Tian, "Integrated process of lignocellulosic biomass torrefaction and pyrolysis for upgrading bio-oil production: a state-of-the-art review," *Renew. Sustain. Energy Rev.*, **107** 20–36

- (2019). doi:10.1016/J.RSER.2019.02.015.
- 37) S. Pang, "Advances in thermochemical conversion of woody biomass to energy, fuels and chemicals," *Biotechnol. Adv.*, **37** (4) 589–597 (2019). doi:10.1016/J.BIOTECHADV.2018.11.004.
 - 38) M.N. Uddin, K. Techato, J. Taweekun, M.M. Rahman, M.G. Rasul, T.M.I. Mahlia, and S.M. Ashrafur, "An overview of recent developments in biomass pyrolysis technologies," *Energies* 2018, Vol. 11, Page 3115, **11** (11) 3115 (2018). doi:10.3390/EN1113115.
 - 39) M. Akbari, A.O. Oyedun, and A. Kumar, "Techno-economic assessment of wet and dry torrefaction of biomass feedstock," *Energy*, **207** 118287 (2020). doi:10.1016/J.ENERGY.2020.118287.
 - 40) P. Brachi, R. Chirone, M. Miccio, and G. Ruoppolo, "Fluidized bed torrefaction of biomass pellets: a comparison between oxidative and inert atmosphere," *Powder Technol.*, **357** 97–107 (2019). doi:10.1016/J.POWTEC.2019.08.058.
 - 41) W.H. Chen, S. Nižetić, R. Sirohi, Z. Huang, R. Luque, A. M. Papadopoulos, R. Sakthivel, X. Phuong Nguyen, and A. Tuan Hoang, "Liquid hot water as sustainable biomass pretreatment technique for bioenergy production: a review," *Bioresour. Technol.*, **344** 126207 (2022). doi:10.1016/J.BIORTECH.2021.126207.
 - 42) S. Kanwal, N. Chaudhry, S. Munir, and H. Sana, "Effect of torrefaction conditions on the physicochemical characterization of agricultural waste (sugarcane bagasse)," *Waste Manag.*, **88** 280–290 (2019). doi:10.1016/J.WASMAN.2019.03.053.
 - 43) C. Zhang, S.H. Ho, W.H. Chen, Y. Xie, Z. Liu, and J.S. Chang, "Torrefaction performance and energy usage of biomass wastes and their correlations with torrefaction severity index," *Appl. Energy*, **220** 598–604 (2018). doi:10.1016/J.APENERGY.2018.03.129.
 - 44) S. Barskov, M. Zappi, P. Buchireddy, S. Dufreche, J. Guillory, D. Gang, R. Hernandez, R. Bajpai, J. Baudier, R. Cooper, and R. Sharp, "Torrefaction of biomass: a review of production methods for biocoal from cultured and waste lignocellulosic feedstocks," *Renew. Energy*, **142** 624–642 (2019). doi:10.1016/J.RENENE.2019.04.068.
 - 45) D. Chen, A. Gao, K. Cen, J. Zhang, X. Cao, and Z. Ma, "Investigation of biomass torrefaction based on three major components: hemicellulose, cellulose, and lignin," *Energy Convers. Manag.*, **169** 228–237 (2018). doi:10.1016/J.ENCONMAN.2018.05.063.
 - 46) H.C. Ong, K.L. Yu, W.H. Chen, M.K. Pillejera, X. Bi, K.Q. Tran, A. Pétrissans, and M. Pétrissans, "Variation of lignocellulosic biomass structure from torrefaction: a critical review," *Renew. Sustain. Energy Rev.*, **152** 111698 (2021). doi:10.1016/J.RSER.2021.111698.
 - 47) C. Zhang, W. Yang, W.H. Chen, S.H. Ho, A. Pétrissans, and M. Pétrissans, "Effect of torrefaction on the structure and reactivity of rice straw as well as life cycle assessment of torrefaction process," *Energy*, **240** 122470 (2022). doi:10.1016/J.ENERGY. 2021.122470.
 - 48) M. Simonic, D. Goricanec, and D. Urbanc, "Impact of torrefaction on biomass properties depending on temperature and operation time," *Sci. Total Environ.*, **740** 140086 (2020). doi:10.1016/J.SCITOTENV. 2020.140086.
 - 49) P.N.Y. Yek, Y.W. Cheng, R.K. Liew, W.A. Wan Mahari, H.C. Ong, W.H. Chen, W. Peng, Y.K. Park, C. Sonne, S.H. Kong, M. Tabatabaei, M. Aghbashlo, and S.S. Lam, "Progress in the torrefaction technology for upgrading oil palm wastes to energy-dense biochar: a review," *Renew. Sustain. Energy Rev.*, **151** 111645 (2021). doi:10.1016/J.RSER.2021.111645.
 - 50) T.A. Mamvura, and G. Danha, "Biomass torrefaction as an emerging technology to aid in energy production," *Heliyon*, **6** (3) e03531 (2020). doi:10.1016/J.HELİYON.2020.E03531.
 - 51) M. Rudolfsson, W. Stelte, and T.A. Lestander, "Process optimization of combined biomass torrefaction and pelletization for fuel pellet production – a parametric study," *Appl. Energy*, **140** 378–384 (2015). doi:10.1016/J.APENERGY. 2014.11.041.
 - 52) L. Shang, N.P.K. Nielsen, J. Dahl, W. Stelte, J. Ahrenfeldt, J.K. Holm, T. Thomsen, and U.B. Henriksen, "Quality effects caused by torrefaction of pellets made from scots pine," *Fuel Process. Technol.*, **101** 23–28 (2012). doi:10.1016/J.FUPROC.2012.03.013.
 - 53) W. Stelte, "Optimization of product specific processing parameters for the production of fuel pellets from torrefied biomass, danish technol," *Inst. Cent. Biomass Biorefinery*, (2014).
 - 54) S. Lata, and R. Kumar, "Disease classification using ecg signals based on r-peak analysis with abc and ann," <https://services.igi-global.com/resolvedoi/resolve.aspx?doi=10.4018/IJECME.2019070105>, **8** (2) 67–86 (1AD). doi:10.4018/IJECME.2019070105.
 - 55) S. Lata, and R. Kumar, "A hybrid approach for ecg signal analysis," *Proc. - IEEE 2018 Int. Conf. Adv. Comput. Commun. Control Networking, ICACCCN 2018*, 971–976 (2018). doi:10.1109/ICACCCN. 2018.8748858.
 - 56) L. Wang, E. Barta-Rajnai, O. Skreiberg, R. Khalil, Z. Czégény, E. Jakab, Z. Barta, and M. Grønli, "Impact of torrefaction on woody biomass properties," *Energy Procedia*, **105** 1149–1154 (2017). doi:10.1016/J. EGYPRO.2017.03.486.
 - 57) B. Grycova, A. Pryszcz, S. Krzack, M. Klinger, and P. Lestinsky, "Torrefaction of biomass pellets using the thermogravimetric analyser," *Biomass Convers. Biorefinery* 2020 116, **11** (6) 2837–2842 (2020). doi:10.1007/S13399-020-00621-4.
 - 58) S.R. Ardiansyah, W. Sjamsuridzal, W. Wardhana, N.B.

- Prihantini, and others, "Analysis of carbon dioxide solubility increasement caused by baffle diameter variation in airlift photobioreactor to growth rate of synechococcus hs-9 biomass," (2021).
- 59) T.O. Olugbade, and O.T. Ojo, "Biomass torrefaction for the production of high-grade solid biofuels: a review," *BioEnergy Res.* 2020 134, **13** (4) 999–1015 (2020). doi:10.1007/S12155-020-10138-3.
- 60) W.H. Chen, C.L. Cheng, P.L. Show, and H.C. Ong, "Torrefaction performance prediction approached by torrefaction severity factor," *Fuel*, **251** 126–135 (2019). doi:10.1016/J.FUEL.2019.04.047.
- 61) A.A. Adeleke, J.K. Odusote, P.P. Ikubanni, O.A. Lasode, M. Malathi, and D. Paswan, "Essential basics on biomass torrefaction, densification and utilization," *Int. J. Energy Res.*, **45** (2) 1375–1395 (2021). doi:10.1002/ER.5884.
- 62) X. Tian, L. Dai, Y. Wang, Z. Zeng, S. Zhang, L. Jiang, X. Yang, L. Yue, Y. Liu, and R. Ruan, "Influence of torrefaction pretreatment on corncobs: a study on fundamental characteristics, thermal behavior, and kinetic," *Bioresour. Technol.*, **297** 122490 (2020). doi:10.1016/J.BIORTECH.2019.122490.
- 63) A. Ozyuguran, A. Akturk, and S. Yaman, "Optimal use of condensed parameters of ultimate analysis to predict the calorific value of biomass," *Fuel*, **214** 640–646 (2018). doi:10.1016/J.FUEL.2017.10.082.
- 64) H.C. Ong, W.H. Chen, Y. Singh, Y.Y. Gan, C.Y. Chen, and P.L. Show, "A state-of-the-art review on thermochemical conversion of biomass for biofuel production: a tg-ftir approach," *Energy Convers. Manag.*, **209** 112634 (2020). doi:10.1016/J.ENCONMAN.2020.112634.
- 65) F. Yao, and H. Wang, "Theoretical analysis on the constitution of calorific values of biomass fuels," *J. Energy Resour. Technol. Trans. ASME*, **141** (2) (2019). doi:10.1115/1.4041468/474695.
- 66) G.A. Tsalidis, and G. Korevaar, "Environmental assessments of scales: the effect of ex-ante and ex-post data on life cycle assessment of wood torrefaction," *Resour. Conserv. Recycl.*, **176** 105906 (2022). doi:10.1016/J.RESCONREC.2021.105906.
- 67) R. García, M.P. González-Vázquez, A.J. Martín, C. Pevida, and F. Rubiera, "Pelletization of torrefied biomass with solid and liquid bio-additives," *Renew. Energy*, **151** 175–183 (2020). doi:10.1016/J.RENENE.2019.11.004.
- 68) Q. Hu, H. Yang, H. Xu, Z. Wu, C.J. Lim, X.T. Bi, and H. Chen, "Thermal behavior and reaction kinetics analysis of pyrolysis and subsequent in-situ gasification of torrefied biomass pellets," *Energy Convers. Manag.*, **161** 205–214 (2018). doi:10.1016/J.ENCONMAN.2018.02.003.
- 69) S.R.H. Siregar, D. Nursani, A. Wiyono, T.P.S.I. Pratiwi, H. Dafiqurrohman, and A. Surjosatyo, "Effect of ratio composition and particle size to pelletizing combination performance of msw and biomass feedstocks," *Evergreen*, **8** (4) 890–895 (2021). doi:10.5109/4742138.
- 70) L.J.R. Nunes, "A case study about biomass torrefaction on an industrial scale: solutions to problems related to self-heating, difficulties in pelletizing, and excessive wear of production equipment," *Appl. Sci.* 2020, Vol. 10, Page 2546, **10** (7) 2546 (2020). doi:10.3390/APP10072546.
- 71) A.M. Orlando, Nasruddin, W. Sjamsuridzal, W. Wardhana, and N.B. Prihantini, "Biomass production and lipid content of leptolyngbya hs-16 grown in bubble column photobioreactors (bcpbr) with air bubbler pore variation," *Evergreen*, **8** (4) 885–889 (2021). doi:10.5109/4742137.
- 72) N.B. Prihantini, N. Rakhmayanti, S. Handayani, W. Sjamsuridzal, W. Wardhana, and Nasruddin, "Biomass production of indonesian indigenous leptolyngbya strain on npk fertilizer medium and its potential as a source of biofuel," *Evergreen*, **7** (4) 593–601 (2020). doi:10.5109/4150512.
- 73) A. Rahman, N.B. Prihantini, and others, "Biomass production and synthesis of biodiesel from microalgae synechococcus hs-9 (cyanobacteria) cultivated using bubble column photobioreactors," *Evergr. Jt. J. Nov. Carbon Resour. Green Asia Strateg.*, **7** (4) 564–570 (2020).
- 74) A. Dhaundiyal, and L. Toth, "Thermal modelling of the torrefaction process using the finite element method," *Environ. Clim. Technol.*, **25** (1) 736–749 (2021).
- 75) W.H. Chen, B.J. Lin, Y.Y. Lin, Y.S. Chu, A.T. Ubando, P.L. Show, H.C. Ong, J.S. Chang, S.H. Ho, A.B. Culaba, A. Pétrissans, and M. Pétrissans, "Progress in biomass torrefaction: principles, applications and challenges," *Prog. Energy Combust. Sci.*, **82** 100887 (2021). doi:10.1016/J.PECS.2020.100887.