**Thermo-physical, Chemical and Structural Modifications in Torrefied Biomass Residues**

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**Abstract**

The study examined the modifications in the thermo-physical and chemical structure of *Tectona grandis* (TK) and *Sorghum bicolour* stalk residues that occurred during the process of torrefaction. The analytical techniques used are Fourier transform infrared spectroscopy (FTIR) and thermogravimetric analysis (TGA) alongside some basic data characterisation techniques. Data from specific FTIR spectra were used quantitatively in the evaluation of total crystalline and lateral order indices (TCI and LOI) for cellulose and syringyl to guaiacyl (S/G) ratio in lignin. The indices and the ratio were applied in monitoring modifications in cellulose crystallinity and lignin structure. The S/G ratio for untreated TK dropped significantly from 0.6 to 0.12 after torrefaction. An appreciable rise in the TCI and LOI was observed for both samples following the thermochemical conversion process. A distinct thermal decomposition pathway, which widen in discrepancy with increasing torrefaction temperature, was established between untreated and torrefied biomass residues via the TGA. The basic data analysis demonstrated a significant rise in the calorific value of torrefied biomass; approximately from an average of 19.1–26.8 MJ/kg.

**Keywords**

FTIR spectroscopy Torrefied biomass TGA Cellulose crystallinity Calorific value

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**Notes**

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**References**

1. 1.

Azeez, A.M., Meier, D., Odermatt, J., Willner, T.: Fast pyrolysis of African and European lignocellulosic biomasses using Py-GC/MS and fluidized bed reactor. Energy Fuels **24**, 2078–2085 (2010)[CrossRef](https://doi.org/10.1021/ef9012856" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Fast%20pyrolysis%20of%20African%20and%20European%20lignocellulosic%20biomasses%20using%20Py-GC%2FMS%20and%20fluidized%20bed%20reactor&author=AM.%20Azeez&author=D.%20Meier&author=J.%20Odermatt&author=T.%20Willner&journal=Energy%20Fuels&volume=24&pages=2078-2085&publication_year=2010)

1. 2.

Oloyede, I., Ayorinde, K.L., Oladele, F.A.: Greening the campus environment: The University of Ilorin experience. 12th General Conference, Association of African Universities, Abuja, Nigeria (2009)[Google Scholar](https://scholar.google.com/scholar?q=Oloyede%2C%20I.%2C%20Ayorinde%2C%20K.L.%2C%20Oladele%2C%20F.A.%3A%20Greening%20the%20campus%20environment%3A%20The%20University%20of%20Ilorin%20experience.%2012th%20General%20Conference%2C%20Association%20of%20African%20Universities%2C%20Abuja%2C%20Nigeria%20%282009%29" \t "_blank)

1. 3.

Food and Agricultural Organization of the United Nations (FAOSTAT). Retrieved from <http://faostat3.fao.org/browse/Q/QC/E> (2015)

1. 4.

Mohammed, Y.S., Mustafa, M.W., Bashir, N., Mokhtar, A.S.: Renewable energy resources for distributed power generation in Nigeria: a review of the potential. Renew. Sustain. Energy Rev. **22**, 257–268 (2013)[CrossRef](https://doi.org/10.1016/j.rser.2013.01.020" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Renewable%20energy%20resources%20for%20distributed%20power%20generation%20in%20Nigeria%3A%20a%20review%20of%20the%20potential&author=YS.%20Mohammed&author=MW.%20Mustafa&author=N.%20Bashir&author=AS.%20Mokhtar&journal=Renew.%20Sustain.%20Energy%20Rev.&volume=22&pages=257-268&publication_year=2013)

1. 5.

van der Stelt, M.J.C., Gerhauser, H., Kiel, J.H.A., Ptasinski, K.J.: Biomass upgrading by torrefaction for the production of biofuels: a review. Biomass Bioenergy **35**, 3748–3762 (2011)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Biomass%20upgrading%20by%20torrefaction%20for%20the%20production%20of%20biofuels%3A%20a%20review&author=MJC.%20Stelt&author=H.%20Gerhauser&author=JHA.%20Kiel&author=KJ.%20Ptasinski&journal=Biomass%20Bioenergy&volume=35&pages=3748-3762&publication_year=2011" \t "_blank)

1. 6.

Rowell, R.M., Pettersen, R., Han, J.S., Rowell, J.S., Tshabalala, M.A.: Cell wall chemistry. In: Rowell, R.M. (ed.) Handbook of Wood Chemistry and Wood Composites, pp. 35–74. CRC Press, Boca Raton (2005)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Cell%20wall%20chemistry&author=RM.%20Rowell&author=R.%20Pettersen&author=JS.%20Han&author=JS.%20Rowell&author=MA.%20Tshabalala&pages=35-74&publication_year=2005" \t "_blank)

1. 7.

Karinkanta, P., Illikainen, M., Niinimäki, J.: Effect of mild torrefaction on pulverization of Norway spruce (*Picea abies*) by oscillatory ball milling: particle morphology and cellulose crystallinity. Holzforschung **68**, 337–343 (2014)[CrossRef](https://doi.org/10.1515/hf-2013-0090" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Effect%20of%20mild%20torrefaction%20on%20pulverization%20of%20Norway%20spruce%20%28Picea%20abies%29%20by%20oscillatory%20ball%20milling%3A%20particle%20morphology%20and%20cellulose%20crystallinity&author=P.%20Karinkanta&author=M.%20Illikainen&author=J.%20Niinim%C3%A4ki&journal=Holzforschung&volume=68&pages=337-343&publication_year=2014)

1. 8.

Na, B., Ahn, B., Lee, J.: Changes in chemical and physical properties of yellow poplar (*Liriodendron tulipifera*) during torrefaction. Wood Sci. Technol. **49**, 257–272 (2015)[CrossRef](https://doi.org/10.1007/s00226-014-0697-1" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Changes%20in%20chemical%20and%20physical%20properties%20of%20yellow%20poplar%20%28Liriodendron%20tulipifera%29%20during%20torrefaction&author=B.%20Na&author=B.%20Ahn&author=J.%20Lee&journal=Wood%20Sci.%20Technol.&volume=49&pages=257-272&publication_year=2015)

1. 9.

Ren, S., Lei, H., Wang, L., Bu, Q., Chen, S., Wu, J.: Thermal behaviour and kinetic study for woody biomass torrefaction and torrefied biomass pyrolysis by TGA. Biosyst. Eng. **116**, 420–426 (2013)[CrossRef](https://doi.org/10.1016/j.biosystemseng.2013.10.003" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Thermal%20behaviour%20and%20kinetic%20study%20for%20woody%20biomass%20torrefaction%20and%20torrefied%20biomass%20pyrolysis%20by%20TGA&author=S.%20Ren&author=H.%20Lei&author=L.%20Wang&author=Q.%20Bu&author=S.%20Chen&author=J.%20Wu&journal=Biosyst.%20Eng.&volume=116&pages=420-426&publication_year=2013)

1. 10.

Wannapeera, J., Worasuwannarak, N.: Examinations of chemical properties and pyrolysis behaviours of torrefied woody biomass prepared at the same torrefaction mass yields. J. Anal. Appl. Pyrol. **115**, 279–286 (2015)[CrossRef](https://doi.org/10.1016/j.jaap.2015.08.007" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Examinations%20of%20chemical%20properties%20and%20pyrolysis%20behaviours%20of%20torrefied%20woody%20biomass%20prepared%20at%20the%20same%20torrefaction%20mass%20yields&author=J.%20Wannapeera&author=N.%20Worasuwannarak&journal=J.%20Anal.%20Appl.%20Pyrol.&volume=115&pages=279-286&publication_year=2015)

1. 11.

Soria, J.A., McDonald, A.G.: Liquefaction of softwoods and hardwoods in supercritical methanol: a novel approach to bio-oil production. In: Baskar, C., Baskar, S., Dhillon, R.S. (eds.) Biomass Conversion: The Interface of Biotechnology, Chemistry and Materials Science, pp. 421–433. Springer, Berlin (2012)[CrossRef](https://doi.org/10.1007/978-3-642-28418-2_13" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Liquefaction%20of%20softwoods%20and%20hardwoods%20in%20supercritical%20methanol%3A%20a%20novel%20approach%20to%20bio-oil%20production&author=JA.%20Soria&author=AG.%20McDonald&pages=421-433&publication_year=2012)

1. 12.

Park, J., Meng, J., Lim, K.H., Rojas, O.J., Park, S.: Transformation of lignocellulosic biomass during torrefaction. J. Anal. Appl. Pyrol. **100**, 199–206 (2013)[CrossRef](https://doi.org/10.1016/j.jaap.2012.12.024" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Transformation%20of%20lignocellulosic%20biomass%20during%20torrefaction&author=J.%20Park&author=J.%20Meng&author=KH.%20Lim&author=OJ.%20Rojas&author=S.%20Park&journal=J.%20Anal.%20Appl.%20Pyrol.&volume=100&pages=199-206&publication_year=2013)

1. 13.

Toptas, A., Yildirim, Y., Duman, G., Yanik, J.: Combustion behavior of different kinds torrefied biomass and their blends with lignite. Bioresour. Technol. **177**, 328–336 (2015)[CrossRef](https://doi.org/10.1016/j.biortech.2014.11.072" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Combustion%20behavior%20of%20different%20kinds%20torrefied%20biomass%20and%20their%20blends%20with%20lignite&author=A.%20Toptas&author=Y.%20Yildirim&author=G.%20Duman&author=J.%20Yanik&journal=Bioresour.%20Technol.&volume=177&pages=328-336&publication_year=2015)

1. 14.

Nhuchhen, D.R.: Prediction of carbon, hydrogen, and oxygen compositions of raw and torrefied biomass using proximate analysis. Fuel **180**, 348–356 (2016)[CrossRef](https://doi.org/10.1016/j.fuel.2016.04.058" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Prediction%20of%20carbon%2C%20hydrogen%2C%20and%20oxygen%20compositions%20of%20raw%20and%20torrefied%20biomass%20using%20proximate%20analysis&author=DR.%20Nhuchhen&journal=Fuel&volume=180&pages=348-356&publication_year=2016)

1. 15.

Tsalidis, G., Joshi, Y., Korevaar, G., de Jong, W.: Life cycle assessment of direct co-firing of torrefied and/or pelletised woody biomass with coal in The Netherlands. J. Clean. Prod. **81**, 168–177 (2014)[CrossRef](https://doi.org/10.1016/j.jclepro.2014.06.049" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Life%20cycle%20assessment%20of%20direct%20co-firing%20of%20torrefied%20and%2For%20pelletised%20woody%20biomass%20with%20coal%20in%20The%20Netherlands&author=G.%20Tsalidis&author=Y.%20Joshi&author=G.%20Korevaar&author=W.%20Jong&journal=J.%20Clean.%20Prod.&volume=81&pages=168-177&publication_year=2014)

1. 16.

Nunes, L.J.R., Matias, J.C.O., Catalão, J.P.S.: A review on torrefied biomass pellets as a sustainable alternative to coal in power generation. Renew. Sustain. Energy Rev. **40**, 153–160 (2014)[CrossRef](https://doi.org/10.1016/j.rser.2014.07.181" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=A%20review%20on%20torrefied%20biomass%20pellets%20as%20a%20sustainable%20alternative%20to%20coal%20in%20power%20generation&author=LJR.%20Nunes&author=JCO.%20Matias&author=JPS.%20Catal%C3%A3o&journal=Renew.%20Sustain.%20Energy%20Rev.&volume=40&pages=153-160&publication_year=2014)

1. 17.

Carrillo, F., Colom, X., Sunol, J.J., Saurina, J.: Structural FTIR analysis and thermal characterisation of lyocell and viscose-type fibres. Eur. Polym. J. **40**, 2229–2234 (2004)[CrossRef](https://doi.org/10.1016/j.eurpolymj.2004.05.003" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Structural%20FTIR%20analysis%20and%20thermal%20characterisation%20of%20lyocell%20and%20viscose-type%20fibres&author=F.%20Carrillo&author=X.%20Colom&author=JJ.%20Sunol&author=J.%20Saurina&journal=Eur.%20Polym.%20J.&volume=40&pages=2229-2234&publication_year=2004)

1. 18.

Akerholm, M., Hinterstoisser, B., Salmen, L.: Characterization of the crystalline structure of cellulose using static and dynamic FT-IR spectroscopy. Carbohydr. Res. **339**, 569–578 (2004)[CrossRef](https://doi.org/10.1016/j.carres.2003.11.012" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Characterization%20of%20the%20crystalline%20structure%20of%20cellulose%20using%20static%20and%20dynamic%20FT-IR%20spectroscopy&author=M.%20Akerholm&author=B.%20Hinterstoisser&author=L.%20Salmen&journal=Carbohydr.%20Res.&volume=339&pages=569-578&publication_year=2004)

1. 19.

Yildiz, S., Gumuskaya, E.: The effects of thermal modification on crystalline structure of cellulose in soft and hardwood. Build. Environ. **42**, 62–67 (2007)[CrossRef](https://doi.org/10.1016/j.buildenv.2005.07.009" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=The%20effects%20of%20thermal%20modification%20on%20crystalline%20structure%20of%20cellulose%20in%20soft%20and%20hardwood&author=S.%20Yildiz&author=E.%20Gumuskaya&journal=Build.%20Environ.&volume=42&pages=62-67&publication_year=2007)

1. 20.

Chen, M., McClure, J.W.: Altered lignin composition in phenylalanine ammonia-lyase-inhibited radish seedlings: implications for seed derived sinapoyl esters as lignin precursors. Phytochemistry **53**, 365–370 (2000)[CrossRef](https://doi.org/10.1016/S0031-9422(99)00531-2" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Altered%20lignin%20composition%20in%20phenylalanine%20ammonia-lyase-inhibited%20radish%20seedlings%3A%20implications%20for%20seed%20derived%20sinapoyl%20esters%20as%20lignin%20precursors&author=M.%20Chen&author=JW.%20McClure&journal=Phytochemistry&volume=53&pages=365-370&publication_year=2000)

1. 21.

Ibrahim, R.H.H., Darvell, L.I., Jones, J.M., Williams, A.: Physicochemical characterization of torrefied biomass. J. Anal. Appl. Pyrol. **103**, 21–30 (2013)[CrossRef](https://doi.org/10.1016/j.jaap.2012.10.004" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Physicochemical%20characterization%20of%20torrefied%20biomass&author=RHH.%20Ibrahim&author=LI.%20Darvell&author=JM.%20Jones&author=A.%20Williams&journal=J.%20Anal.%20Appl.%20Pyrol.&volume=103&pages=21-30&publication_year=2013)

1. 22.

Zheng, A., Zhao, Z., Chang, S., Huang, Z., Wang, X., He, F., Li, H.: Effect of torrefaction on structure and fast pyrolysis behavior of corncobs. Bioresour. Technol. **128**, 370–377 (2013)[CrossRef](https://doi.org/10.1016/j.biortech.2012.10.067" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Effect%20of%20torrefaction%20on%20structure%20and%20fast%20pyrolysis%20behavior%20of%20corncobs&author=A.%20Zheng&author=Z.%20Zhao&author=S.%20Chang&author=Z.%20Huang&author=X.%20Wang&author=F.%20He&author=H.%20Li&journal=Bioresour.%20Technol.&volume=128&pages=370-377&publication_year=2013)

1. 23.

Zheng, A., Zhao, Z., Chang, S., Huang, Z., Zhao, K., Wei, G., He, F., Li, H.: Comparison of the effect of wet and dry torrefaction on chemical structure and pyrolysis behavior of corncobs. Bioresour. Technol. **176**, 15–22 (2015)[CrossRef](https://doi.org/10.1016/j.biortech.2014.10.157" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Comparison%20of%20the%20effect%20of%20wet%20and%20dry%20torrefaction%20on%20chemical%20structure%20and%20pyrolysis%20behavior%20of%20corncobs&author=A.%20Zheng&author=Z.%20Zhao&author=S.%20Chang&author=Z.%20Huang&author=K.%20Zhao&author=G.%20Wei&author=F.%20He&author=H.%20Li&journal=Bioresour.%20Technol.&volume=176&pages=15-22&publication_year=2015)

1. 24.

Hill, S.J., Grigsby, W.J., Hall, P.W.: Chemical and cellulose crystallite changes in *Pinus radiata* during torrefaction. Biomass Bioenergy **56**, 92–98 (2013)[CrossRef](https://doi.org/10.1016/j.biombioe.2013.04.025" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Chemical%20and%20cellulose%20crystallite%20changes%20in%20Pinus%20radiata%20during%20torrefaction&author=SJ.%20Hill&author=WJ.%20Grigsby&author=PW.%20Hall&journal=Biomass%20Bioenergy&volume=56&pages=92-98&publication_year=2013)

1. 25.

Balogun, A.O., Lasode, O.A., McDonald, A.G.: Thermo-analytical and physico-chemical characterization wood and non-woody biomass from an agro-ecological zone in Nigeria. BioResources **9**, 5099–5113 (2014)[CrossRef](https://doi.org/10.15376/biores.9.3.5099-5113" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Thermo-analytical%20and%20physico-chemical%20characterization%20wood%20and%20non-woody%20biomass%20from%20an%20agro-ecological%20zone%20in%20Nigeria&author=AO.%20Balogun&author=OA.%20Lasode&author=AG.%20McDonald&journal=BioResources&volume=9&pages=5099-5113&publication_year=2014)

1. 26.

Lasode, O.A., Balogun, A.O., McDonald, A.G.: Torrefaction of some Nigerian lignocellulosic resources and decomposition kinetics. J. Anal. Appl. Pyrol. **109**, 47–55 (2014)[CrossRef](https://doi.org/10.1016/j.jaap.2014.07.014" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Torrefaction%20of%20some%20Nigerian%20lignocellulosic%20resources%20and%20decomposition%20kinetics&author=OA.%20Lasode&author=AO.%20Balogun&author=AG.%20McDonald&journal=J.%20Anal.%20Appl.%20Pyrol.&volume=109&pages=47-55&publication_year=2014)

1. 27.

American Standard of Testing and Materials. ASTM D1102-84. Standard test method for ash in wood, West Conshohocken, Pennsylvania, ASTM International (2007)[Google Scholar](https://scholar.google.com/scholar?q=American%20Standard%20of%20Testing%20and%20Materials.%20ASTM%20D1102-84.%20Standard%20test%20method%20for%20ash%20in%20wood%2C%20West%20Conshohocken%2C%20Pennsylvania%2C%20ASTM%20International%20%282007%29)

1. 28.

British Standards Institution. BS EN 15148:2009. Solid biofuels: determination of the content of volatile matter. London, BSI[Google Scholar](https://scholar.google.com/scholar?q=British%20Standards%20Institution.%20BS%20EN%2015148%3A2009.%20Solid%20biofuels%3A%20determination%20of%20the%20content%20of%20volatile%20matter.%20London%2C%20BSI)

1. 29.

Friedl, A., Padouvas, E., Rotter, H., Varmuza, K.: Prediction of heating values of biomass fuel from elemental composition. Anal. Chem. **554**, 191–198 (2005)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Prediction%20of%20heating%20values%20of%20biomass%20fuel%20from%20elemental%20composition&author=A.%20Friedl&author=E.%20Padouvas&author=H.%20Rotter&author=K.%20Varmuza&journal=Anal.%20Chem.&volume=554&pages=191-198&publication_year=2005" \t "_blank)

1. 30.

Faix, O.: Fourier transform infrared spectroscopy. In: Lin, S.Y., Dence, C.W. (eds.) Methods in Lignin Chemistry, pp. 83–109. Springer, Berlin (1992)[CrossRef](https://doi.org/10.1007/978-3-642-74065-7_7" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Fourier%20transform%20infrared%20spectroscopy&author=O.%20Faix&pages=83-109&publication_year=1992)

1. 31.

Gaur, S., Reed, T.B.: Thermal Data for Natural Synthetic Fuels. Marcel Dekker, New York (1998)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Thermal%20Data%20for%20Natural%20Synthetic%20Fuels&author=S.%20Gaur&author=TB.%20Reed&publication_year=1998" \t "_blank)

1. 32.

Balogun, A.O., Lasode, O.A., Li, H., McDonald, A.G.: Fourier transform infrared (FTIR) study and thermal decomposition kinetics of *Sorghum bicolour* glume and *Albizia pedicellaris* residues. Waste Biomass Valoriz. **6**, 109–116 (2015)[CrossRef](https://doi.org/10.1007/s12649-014-9318-3" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Fourier%20transform%20infrared%20%28FTIR%29%20study%20and%20thermal%20decomposition%20kinetics%20of%20Sorghum%20bicolour%20glume%20and%20Albizia%20pedicellaris%20residues&author=AO.%20Balogun&author=OA.%20Lasode&author=H.%20Li&author=AG.%20McDonald&journal=Waste%20Biomass%20Valoriz.&volume=6&pages=109-116&publication_year=2015)

1. 33.

Sharma, R.K., Wooten, J.B., Baliga, V.L., Lin, X., Chan, W.G., Hajaligol, M.R.: Characterization of chars from pyrolysis of lignin. Fuel **83**, 1469–1482 (2004)[CrossRef](https://doi.org/10.1016/j.fuel.2003.11.015" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Characterization%20of%20chars%20from%20pyrolysis%20of%20lignin&author=RK.%20Sharma&author=JB.%20Wooten&author=VL.%20Baliga&author=X.%20Lin&author=WG.%20Chan&author=MR.%20Hajaligol&journal=Fuel&volume=83&pages=1469-1482&publication_year=2004)

1. 34.

Santos, J.: Mechanical behavior of Eucalyptus wood modified by heat. Wood Sci. Technol. **34**, 39–43 (2000)[CrossRef](https://doi.org/10.1007/s002260050006" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Mechanical%20behavior%20of%20Eucalyptus%20wood%20modified%20by%20heat&author=J.%20Santos&journal=Wood%20Sci.%20Technol.&volume=34&pages=39-43&publication_year=2000)

1. 35.

Carrasco, F., Roy, C.: Kinetic study of dilute acid prehydrolysis xylan containing biomass. Wood Sci. Technol. **26**, 189–208 (1992)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Kinetic%20study%20of%20dilute%20acid%20prehydrolysis%20xylan%20containing%20biomass&author=F.%20Carrasco&author=C.%20Roy&journal=Wood%20Sci.%20Technol.&volume=26&pages=189-208&publication_year=1992" \t "_blank)

1. 36.

Reiniati, I., Osman, N.B., McDonald, A.G., Laborie, M.-P.: Linear viscoelasticity of hot-pressed hybrid poplar relates to densification and to the in situ molecular parameters of cellulose. Ann. For. Sci. **72**, 693–703 (2015)[CrossRef](https://doi.org/10.1007/s13595-014-0421-1" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Linear%20viscoelasticity%20of%20hot-pressed%20hybrid%20poplar%20relates%20to%20densification%20and%20to%20the%20in%20situ%20molecular%20parameters%20of%20cellulose&author=I.%20Reiniati&author=NB.%20Osman&author=AG.%20McDonald&author=M-P.%20Laborie&journal=Ann.%20For.%20Sci.&volume=72&pages=693-703&publication_year=2015)

1. 37.

Weimer, P.J., Hackey, J.M., French, A.D.: Effects of chemical treatments and heating on the crystallinity of celluloses and their implications for evaluating the effect of crystallinity on cellulose biodegradation. Biotechnol. Bioeng. **48**, 169–178 (1995)[CrossRef](https://doi.org/10.1002/bit.260480211" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Effects%20of%20chemical%20treatments%20and%20heating%20on%20the%20crystallinity%20of%20celluloses%20and%20their%20implications%20for%20evaluating%20the%20effect%20of%20crystallinity%20on%20cellulose%20biodegradation&author=PJ.%20Weimer&author=JM.%20Hackey&author=AD.%20French&journal=Biotechnol.%20Bioeng.&volume=48&pages=169-178&publication_year=1995)

1. 38.

Bhuiyan, M.T.R., Hirai, N., Sobue, N.: Changes of crystallinity in wood cellulose by heat treatment under dried and moist conditions. J. Wood Sci. **46**, 431–436 (2000)[CrossRef](https://doi.org/10.1007/BF00765800" \t "_blank)[Google Scholar](http://scholar.google.com/scholar_lookup?title=Changes%20of%20crystallinity%20in%20wood%20cellulose%20by%20heat%20treatment%20under%20dried%20and%20moist%20conditions&author=MTR.%20Bhuiyan&author=N.%20Hirai&author=N.%20Sobue&journal=J.%20Wood%20Sci.&volume=46&pages=431-436&publication_year=2000)

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