

Preprocessing and Pretreatment Technologies for Addressing Some of the Biomass Supply Chain Logistics Challenges

Tumuluru Jaya Shankar
Southwestern Cotton Ginning Research Laboratory
United States Department of Agriculture, Agricultural Research Service
Las Cruces, NEW Mexico, USA, 88001
Email: Jayashankar.Tumuluru@usda.gov
Phone: 575-526-6381

Biomass Challenges

The increased climate change crisis, ever-decreasing reserves of fossil fuel resources, and concerns regarding the increased carbon dioxide and methane emissions necessitate clean, sustainable, and renewable energy sources such as biomass. Biomass, in its raw form, lacks the qualities necessary for cost-efficient bioenergy production, especially in bulk and energy densities. Biomass quality characteristics, such as moisture, particle size and distribution, and chemical and biochemical composition, depend upon the biomass type, harvesting methods, storage, preprocessing, and pretreatment unit operations conducted on the biomass feedstocks. These physical properties, chemical, and biochemical composition of biomass supplied have to meet certain specifications for operating at the biorefineries at the designed capacities and producing biofuels and bioproducts at scale that are economically viable. The challenge is that these properties are highly variable for different bioenergy-based feedstocks and depend on various factors within the supply chain.

Supply chain factors that impact the quality and supply of reliable feedstocks to the biorefinery are spatial and temporal distribution, which influence transportation, handling, and storage logistics; environmental factors, such as weather, harvesting times, and locations; harvested material state, such as moisture content, energy content, contamination, material format; and material attributes including rheological properties such as density, flowability, elastic properties, bulk and particle density and thermal properties. The properties of biomass for producing biofuels/bioproducts are also highly dependent on the preprocessing and pretreatments, which are part of supply chain logistics. These pretreatment and preprocessing unit operations should be integrated with the downstream system designs and optimized to supply a feedstock that meets the biorefinery storage and handling systems while maximizing biofuels and bioproducts production. Table 1 indicates the various challenges in the biomass supply chain.

Table 1: Potential challenges in the biomass supply chain

Challenge	Description
Availability of biomass feedstocks	Limited quantities of high-quality woody biomass are available for biofuel production. It is also expensive and not always sustainable.
Ash content	Residues from forests and agriculture have higher concentrations of micro-elements such as potassium, calcium, magnesium, and ash.
Bulk and energy density	Low bulk and energy densities of biomass results in high storage costs and low transportation efficiency
Flowability	The raw and ground biomass has two-dimensional irregular particle size and shape and low bulk density, which creates storage, transportation, handling, and feeding challenges.

Storage degradation	High and variable biomass moisture during harvesting and storage degrades the biomass quality and adversely impacts the downstream conversion.
---------------------	--

Biomass Supply Chain Unit Operations

Generally, feedstock supply systems can be grouped into five processes (Hess et al., 2003): a) biomass production, b) harvest and collection, c) storage and queuing, d) preprocessing and pretreatments, and e) transportation (Hess & Tumuluru, 2024). Biomass production involves producing biomass feedstocks up to the point of harvest. The factors that impact production are the selection of feedstock type, land-use issues, policy issues, and agronomic practices, which affect yield, harvest, and collection operations. Harvest and collection encompass all operations associated with getting the biomass from its production source to the queuing location, usually the landing site. The biomass is packed in bales at the harvest location for herbaceous biomass, and woody biomass includes felling and forwarding/yarding. Storage and queuing include operations that focus on making biomass aerobically stable and preventing quality loss. These often include protection from the environment and must accommodate seasonal harvest times, limited operational windows, variable yields, and delivery schedules (Figure 1). Preprocessing and pretreatments may occur before and facilitate transportation or after transport, transforming the biomass into the physical form or chemical and biochemical composition the biorefinery requires for efficient conversion. In the woody or herbaceous biomass supply chain systems, preprocessing can include simple unit operations such as chipping or grinding. Transportation accomplishes moving the biomass from one point (often the harvest or preprocessing location) to another throughout the supply system and may include unit operations such as loading, receiving, and handling, either at the harvest location or the biorefinery. Figure 2 shows the transportation of woody biomass from the harvest site (Rials et al., 2021). The modes of transportation, such as truck, rail, and ship or pipeline, are generally well-defined for respective locations and depend highly on the material's form and bulk and energy densities. The challenge with transportation is that the harvested biomass can only be transported shorter distances economically due to lack of format and low bulk density, even after grinding or chipping. These issues, especially lack of format, can result in feed handling issues and limit the biorefineries from operating at the designed capacities. Figure 3 shows the bridging of the drop chutes and screw conveyors during corn stover handling (Tumuluru et al., 2021). Figure 4 shows flow diagrams of simple supply systems for woody and herbaceous biomass to biorefineries (Hess & Tumuluru, 2024).



Corn stover bales

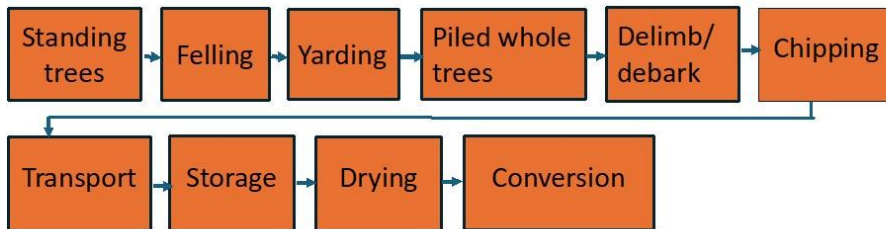
Figure 1: Harvested herbaceous biomass storage.



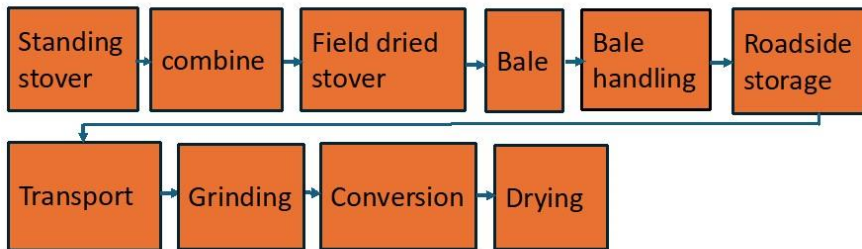
Figure 2: Transportation of woody biomass.



Figure 3: Corn stover bridging in a) storage bins, b) drop chute, and c) jamming in a screw conveyor.



a) Woody biomass supply system



b) Herbaceous biomass supply system

Figure 4: Simple biomass supply chain systems.

Advanced Biomass Feedstock Supply Chain Design

Researchers at the Idaho National Laboratory, Idaho Falls, Idaho, USA, developed an advanced uniform-format feedstock supply chain design concept to transport biomass feedstocks efficiently (Hess & Tumuluru, 2024). This system is based on the high-capacity and high-efficiency supply systems already

existing for other commodities (e.g., grain and petroleum crude) (Figure 5). However, it may not be suitable when handling low-density and aerobically unstable biomass such as crop or forest residues. In order to make the biomass work in a uniform feedstock supply system, biomass needs to be preprocessed using technologies like pelleting, briquetting, and cubing to produce a commodity-like product that is flowable, aerobically stable format, high-density (i.e., pellets, briquettes, and cubes) which are suitable for long-distance transportation. These densified products can work efficiently in biomass storage, transportation, handling, and feeding systems. For example, wood pellets are produced in millions of tons in the United States and Canada and transported intercontinental for power generation in commercial power plants.

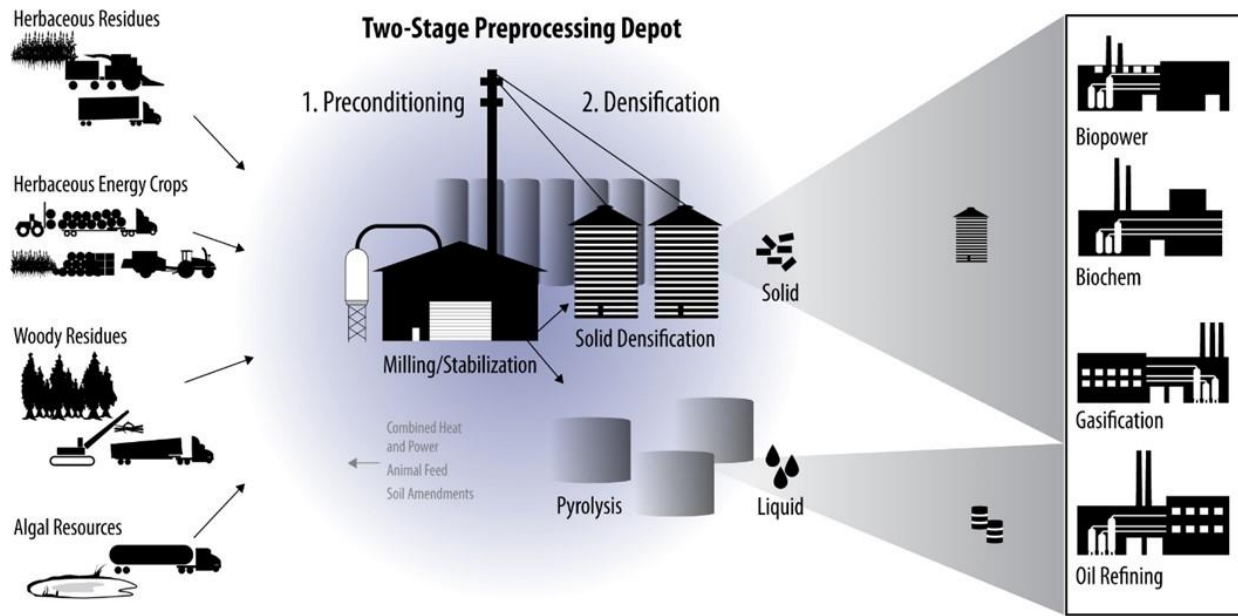


Figure 5. Uniform-format biomass feedstock supply system.

Technologies to Support Advanced Feedstock Supply Chain Design

Mechanical Preprocessing

Typically, biomasses after harvesting and grinding have lower densities, about 50-100 kg/m³, and are not economically feasible for long-distance transportation. Also, the fibrous and elastic nature of the biomass materials creates feed handling challenges. One way to address this is to preprocess this material to increase the bulk density. Mechanical preprocessing such as grinding and densification not only improves the transportation efficiency but also improves the handling and conveyance efficiencies of the biomass feedstock throughout the supply system and biorefinery infeed by providing consistent particle size distribution for improved feedstock uniformity and density, fractionation of the structural components during which interns improve the compositional quality, and meeting the specification of the pre-determined conversion technology and supply system (Tumuluru et al., 2011). Studies showed that wood and herbaceous biomass can be converted into densified products such as pellets and briquettes. Figure 6 shows ground and densified products produced using agricultural residues.



Figure 6: Examples of mechanically preprocessed corn stover (Tumuluru, 2019, 2019a)

Advances in Biomass Preprocessing Technologies

There is much emphasis on developing novel preprocessing technologies to make biomass preprocessing energy-efficient and reduce processing costs. Three new technologies, fractional milling, high moisture pelleting, and low-temperature drying, were tested to convert variable moisture agricultural and forest residues into pellets at a low cost (Tumuluru & Yancey, 2018). Figure 7 shows the novel 2-stage grinding process, high moisture pelleting, and low-temperature drying technologies developed and tested. These technologies should help provide a more economical process model for biomass conversion to fuels and power.

Fractional Milling

The current two-stage grinding method sends all the material to the stage-2 grinder to ensure no oversized particles. Fractional milling uses screens to separate the material during the two-stage grinding that already meets the size requirements of the process between the Stage-1 and -2 grinders to produce a more uniform (relative to particle size) product with less energy consumed. This avoids redundant or overprocessing of the biomass and saves energy. The other major advantage of fractional milling is that it results in tighter particle size distribution with reduced fines. Tumuluru and Yancey (2018), in their studies on corn stover during two-stage grinding, found that 40-55 % of the biomass after stage-1 grinding already met the specifications of the size required for pelleting (6.35 mm) and did not need to be processed again.

High Moisture Pelleting and Low Temperature Drying

In biomass pellet production, drying is the most energy-intensive unit operation. Current pelleting processes use low moisture biomass in the 10-12 % (w.b.). The woody and herbaceous biomasses that

come with variable moisture content are predried in high-temperature rotary dryers, which typically operate at about 200 °C to reduce the moisture content. The capital costs associated with these drying processes are also high. The other disadvantage of high-temperature drying is the emission of volatile organic compounds and extractives. Tumuluru (2016) reasoned that these emissions are a severe concern for humans and the environment as they result in the formation of photo-oxidants, which are harmful if they are inhaled (impact sensitive parts of the lungs) and can disturb photosynthesis, thereby damaging forests and crops. Tumuluru (2014, 2016, 2022) tested high-moisture pelleting of woody and herbaceous biomass, eliminating the high-temperature drying step. In this process, biomasses with variable moisture content ranging from 10% to 30 % (w.b.) are pelleted, and the high-moisture pellets are further dried in low-temperature dryers. Low-temperature dryers are available at high capacities and lower cost and do not need high-quality heat. Tumuluru (2023) demonstrated the high moisture pelleting process using high-moisture corn stover bales without drying and concluded that the energy required for high moisture pelleting of high moisture corn stover bales was less than 60-70 % compared to just drying the biomass in high-temperature rotary dryers. According to Lamers et al. (2015), replacing the rotary dryer with a grain dryer is one of the main reasons for the reduced pellet production cost. The requirement of ultra-high air temperature in rotary dryers causes a higher drying cost when compared to crossflow or mixed-flow grain dryers, which operate between 32 and 90 °C, depending on the dried material. Tumuluru et al. (2019b) showed that high fractional milling, high moisture pelleting, and low-temperature drying reduce the cost of pelleting by more than 50 % (Figure 8).

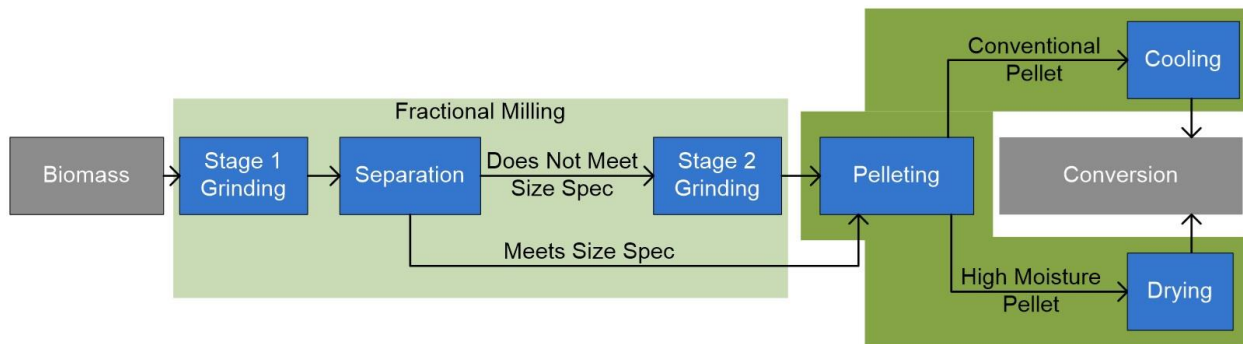


Figure 7: Flow diagram of advanced biomass preprocessing systems (fractional milling, high-moisture pelleting, and low-temperature drying).

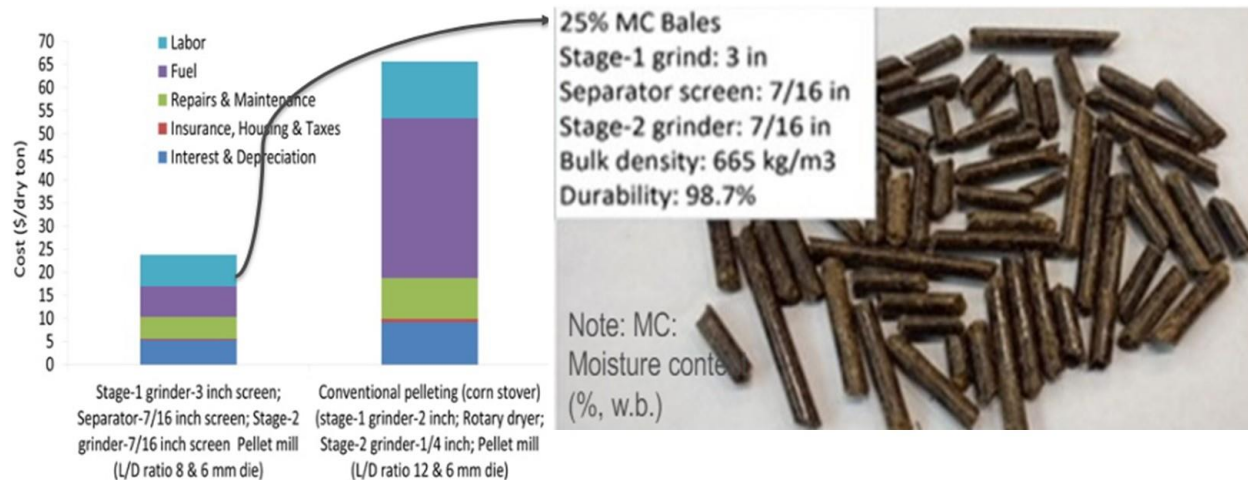
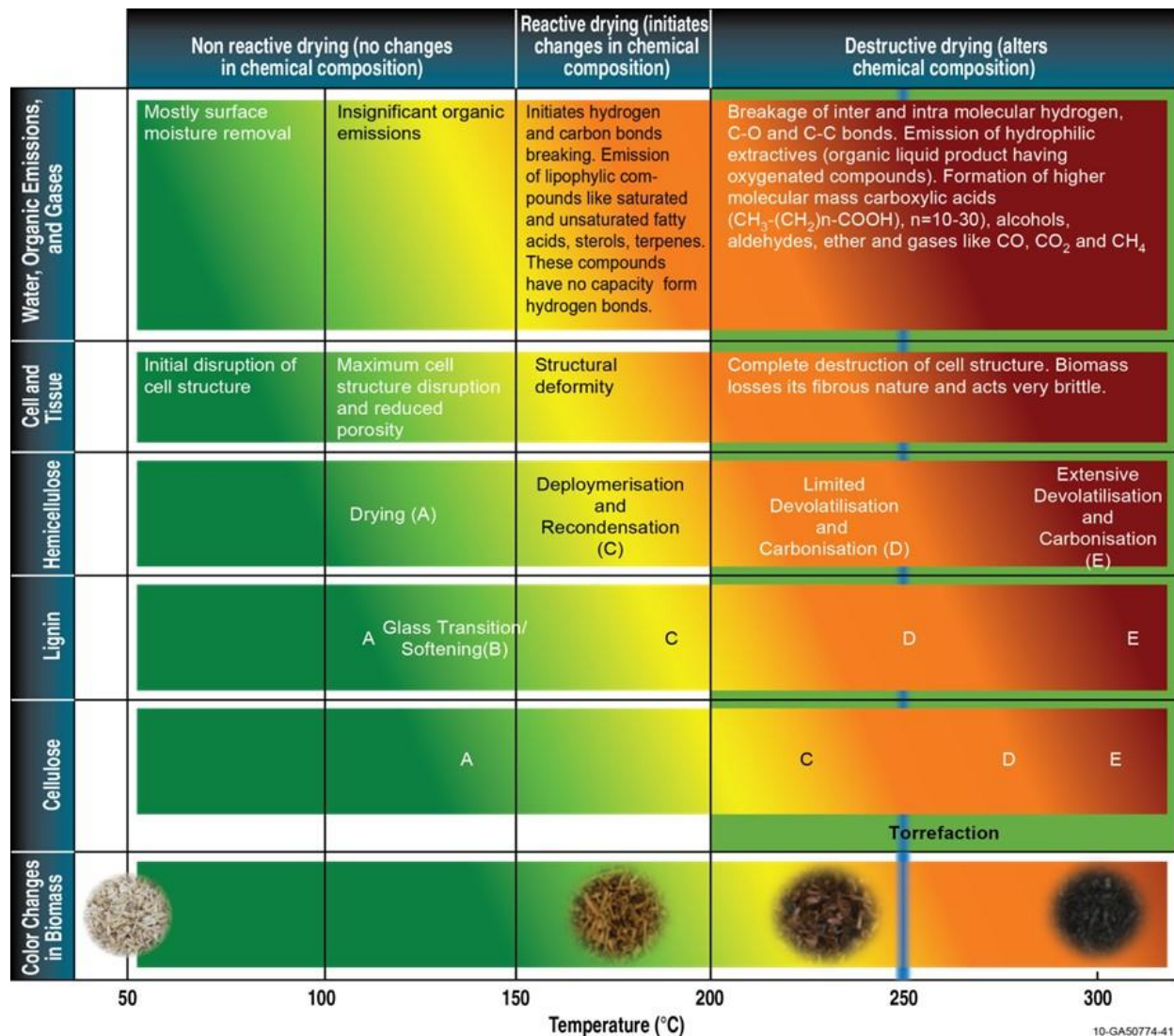


Figure 8: Cost and quality of corn stover pellets produced using advanced preprocessing technologies.

Thermal Pretreatment Technology

Deep drying and torrefaction is a thermal pretreatment technology that helps convert biomass into energy-dense products and improve the chemical composition (Tumuluru et al., 2011b; Tumuluru et al., 2021a). During torrefaction, the raw biomass is heated in the temperature range of 150-300°C in an inert environment. Figure 9 shows the various changes in the biomass at various temperature regimes ranging from 50-150°, 150-200°, and 200-300° C and labels the regimes as non-reactive, reactive, and destructive drying zones (Tumuluru et al., 2011b). In the non-reactive zone, most of the moisture in the biomass is lost; in the reactive zone, some composition changes happen due to the initiation of breakage of the carbon and hydrogen bonds, which results in the emission of lipophilic compounds. In the destructive drying (200–300°C) temperature regime, which is also the torrefaction temperature zone, most of the inter- and intra-molecular hydrogen bonds and C-C and C-O bonds breakage happens and results in the formation of hydrophilic extractives, carboxylic acids, alcohols, aldehydes, ether, and gases like CO, CO₂, and CH₄. At these temperatures, cell structure is destroyed; biomass loses its fibrous nature and becomes brittle. Figure 10 shows the color changes in the lodgepole pine biomass at different temperature regimes (Tumuluru, 2016a). In this temperature range, most moisture and low energy content volatiles are removed from biomass, which becomes energy-dense. Improved physical and chemical composition in the biomass makes it suitable for thermochemical conversion applications such as pyrolysis and gasification. Tumuluru (2016a) studied how the hydrogen-to-carbon (H/C) and oxygen-to-carbon (O/C) ratios change when lodgepole pine is torrefied at different temperature regimes (Figure 11). This study indicated that higher torrefaction temperatures significantly change the H/C and O/C ratios of the biomass and move it closer to commercial coals. The torrefaction process opens more lignin-active sites by breaking down the hemicellulose matrix and forming fatty unsaturated structures, which can create better binding for biomass particles during compression and extrusion. Many studies have indicated that, compared to raw biomass pelletization, the pressure and energy consumption required can be reduced by a factor of 2 when the material is densified at a temperature of 225°C (Figure 12) (Tumuluru et al., 2011b). The breakage of the hydroxyl groups during torrefaction makes torrefied biomass hydrophobic and significantly improves the storage stability. Figure 13 compares the behavior of raw and torrefied pellets when immersed in water. It was evident that torrefied pellets retain their structure and integrity even after 30 minutes, whereas raw pellets disintegrate entirely in the water. As most low-energy-content volatiles are removed during torrefaction, storing off-gas emissions such as carbon monoxide, carbon dioxide, and methane are also lower (Tumuluru et al., 2015). Figure 14 shows the carbon monoxide emissions from different ground, pelleted, and torrefied biomass, where the torrefied wood chips have the lowest compared to ground switchgrass, wood chips, and wood pellets.



10-GA50774-41

Figure 9: Impact of thermal pretreatment on the biomass components.

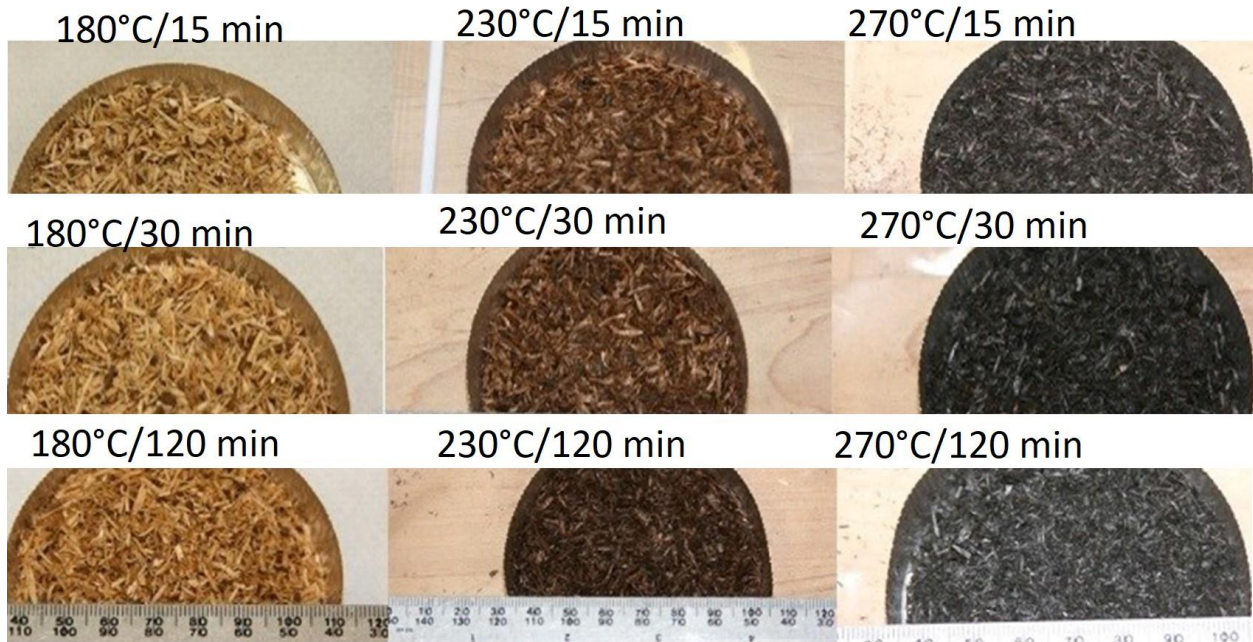


Figure 10: Corn stover torrefied at different temperature regimes.

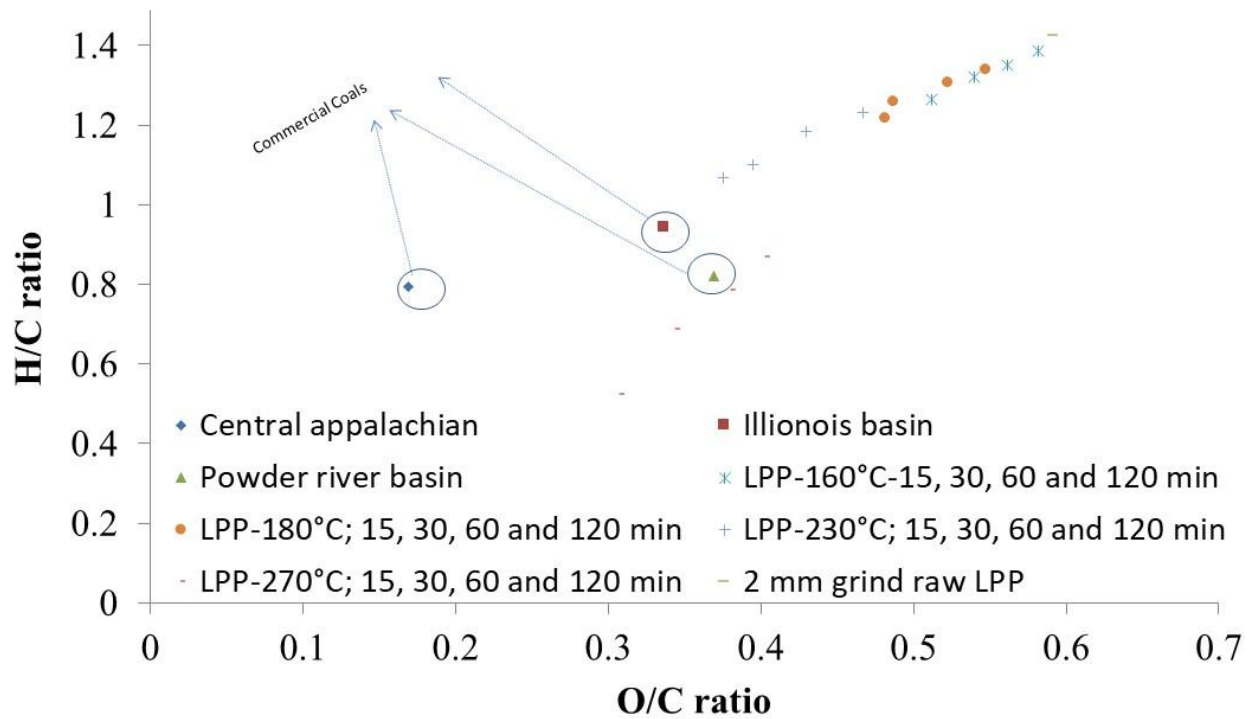


Figure 11: Hydrogen to carbon (H/C) and oxygen to carbon ratio (O/C) changes in lodgepole pine after deep drying and torrefaction.



Figure 12: Torrefaction and densification process



Figure 13: Behaviour of raw and torrefied pellets immersed in water.

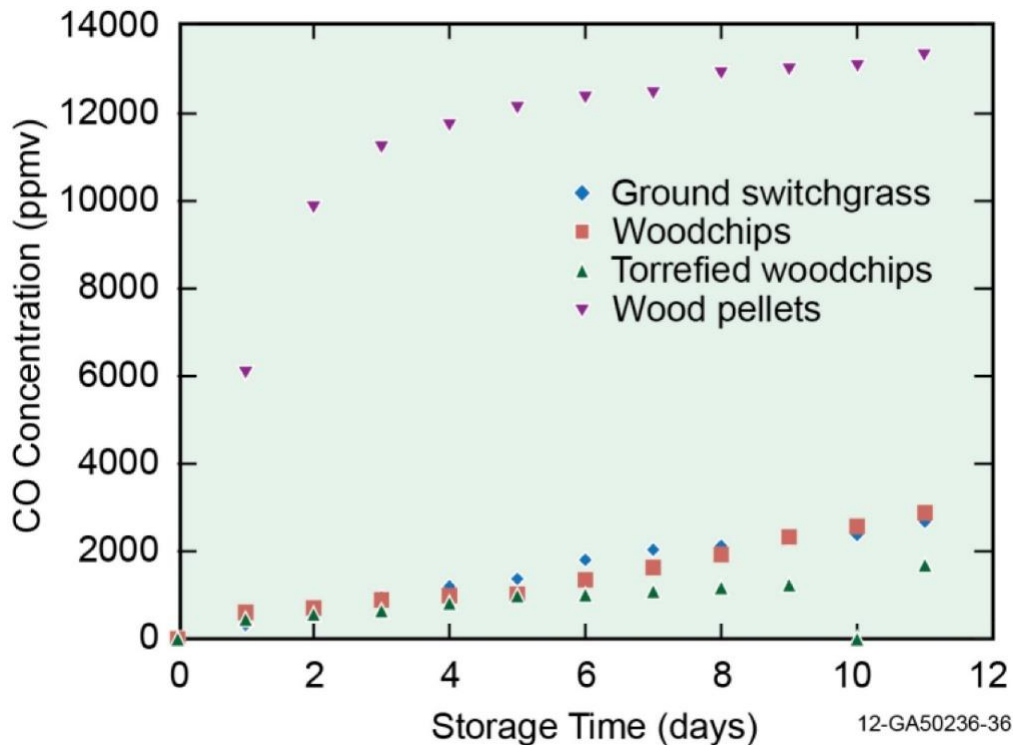


Figure 14: Carbon monoxide emission from ground, pelleted, and torrefied biomass.

Densification and Torrefaction Impact on the Biomass Supply Chain Logistics

Low Moisture: Reduced moisture level for downstream thermochemical conversion processes, reduced transportation costs associated with moving unwanted water, and prevention of biomass decomposition and moisture absorption during storage and transportation.

Improved Bulk Density: Mechanical densification increases the bulk density four to five-fold compared to raw biomass. Mechanical densification systems such as pellet mills, briquette presses, and cubers convert biomass into a commodity product, making it easy to store, handle, and feed in the bioenergy feed supply system. Densified products such as wood pellets and briquettes have low moisture content, making them aerobically stable at different storage temperatures and relative humidities. Also, mechanical densification is a thermo-mechanical process that results in the fractionation of the biomass structural components and improves the compositional quality.

Improved Storability: The loss of OH groups during torrefaction makes the biomass hydrophobic. This will reduce the need for expensive covered storage and help biomass retain most chemical composition and energy properties during storage and transportation.

Followability: After grinding, torrefied biomass has a more uniform particle size and shape, improving flowability and making it easier to handle in the existing high-volume transportation systems.

Improved Energy Density: Torrefaction removes moisture and low-energy volatiles and retains most energy content. This increases the heating value and improves the combustion efficiency of biomass.

Reduces Logistics Costs: Torrefaction and densification increase energy and bulk density, reducing logistics costs. Studies of the breakeven distance transportation of various biomass feedstocks indicated that torrefied pellets had the highest transportation potential.

Reduced Preprocessing Cost: Torrefaction makes biomass brittle due to loss of moisture and low energy content volatiles. This makes biomass easier to grind and reduces the grinding energy by about 50-70 % compared to raw biomass. Mechanical densification studies indicated that compared to raw biomass densification, the required pressure and energy consumption can be reduced by a factor of 2 when the material is densified at a temperature of 225°C.

Reduced Variability: Torrefied biomass has a uniform and consistent moisture (less than 3 %), pulverizes more evenly, produces more uniform and spherical particle size, and with more consistent chemical properties (proximate and ultimate composition) which aids even blending with other plant fractions.

Reduced Off-Gases emissions: Storage of off-gases such as CO, CO₂, and CH₄ is less for torrefied wood chips than non-torrefied wood chips, ground switchgrass, and commercial wood pellets.

References

- Hess, J.R et al. (2003) Roadmap for agriculture biomass feedstock supply in the United States. DOE/NE-ID-11129, Rev 1. US Department of Energy, Washington, DC (<https://doi.org/10.2172/963109>)
- Hess, J.R. and Tumuluru, J.S. (2024). Biomass Supply Chain Logistics: Challenges and Technological Advancements. In: Bisaria, V. (eds) Handbook of Biorefinery Research and Technology. Springer, Dordrecht (https://doi.org/10.1007/978-94-007-6724-9_46-1).
- Lamers, P., Roni, M.S., Tumuluru, J.S., Jacobson, J.J., Cafferty, K.G., Hansen, J.K., Kenney, K., Teymouri, F. & Bals, B. (2015). Techno-economic analysis of decentralized biomass processing depots. *Bioresource Technology*, 194, 205–213.
- Rials, T G., McDonald, T., Taylor, S., Gallagher, T., Labbe, N., Fasina, O., Adhikari, S., Young, T., Tumuluru, J.S., Jackson, S., Kelley, S., Park, S., English, B., & Yu, E. (2021). Next Generation Logistics Systems for Delivering Optimal Biomass Feedstocks to Biorefining Industries in the Southeastern U.S., United States (<https://doi.org/10.2172/1832883>).
- Tumuluru, J. S. & Heikkila, D. J. (2019). Biomass Grinding Process Optimization Using Response Surface Methodology and a Hybrid Genetic Algorithm. *Bioengineering*, 6(1), 12.
- Tumuluru, J. S. (2014). Effect of process variables on the density and durability of the pellets made from high moisture corn stover. *Biosystems Engineering*, 119, 44-57.
- Tumuluru, J. S. (2016a). Effect of Deep Drying and Torrefaction Temperature on Proximate, Ultimate Composition, and Heating Value of 2-mm Lodgepole Pine (*Pinus contorta*) Grind. *Bioengineering*, 3(2), 16.
- Tumuluru, J. S. (2019a). Effect of moisture content and hammer mill screen size on the briquetting characteristics of woody and herbaceous biomass. *KONA Powder Particle Journal*, 36, 241–251.
- Tumuluru, J. S. (2023). High-moisture pelleting of corn stover using pilot- and commercial-scale systems: Impact of moisture content, L/D ratio and hammer mill screen size on pellet quality and energy consumption. *Biofuels, Bioproducts and Biorefining*, 17(5), 1156-1173.
- Tumuluru, J. S., Fillerup, E., Kane, J. & Murray, D. J. (2019b). 1.2.1.2 Biomass Engineering: Size reduction, drying and densification of high moisture biomass, US Department of Energy (DOE) Bioenergy Technologies Office (BETO) 2019 Project Peer Review, Technology Area Session: Feedstock Supply & Logistics March 2019, (https://www.energy.gov/sites/prod/files/2019/04/f61/Size%20Reduction%2C%20Drying%20and%20Densification%20of%20High%20Moisture%20Biomass_NL0026654.pdf).

- Tumuluru, J. S., Ghiasi, B., Soelberg, N. R., & Sokhansanj, S. (2021a). Biomass Torrefaction Process, Product Properties, Reactor Types, and Moving Bed Reactor Design Concepts. *Frontiers in Energy Research*, 9, 728140.
- Tumuluru, J. S., Hernandez, S., Austin, B., Fillerup, E., Kane, J., Murray, D.J., Batchu, R & Lacey, J. (2021). 1.2.1.2 Biomass Size Reduction, Drying and Densification. DOE Bioenergy Technologies Office (BETO), 2021 Project Peer Review, March, 2021, Feedstock Technologies Program (<https://www.energy.gov/sites/default/files/2021-04/beto-15-peer-review-2021-feedstk-tumuluru.pdf>).
- Tumuluru, J. S., Sokhansanj, S., Hess, J. R., Wright, C. T., and Boardman, R. D. (2011b). Review: A Review on Biomass Torrefaction Process and Product Properties for Energy Applications. *Industrial Biotechnology*, 7 (5), 384–401.
- Tumuluru, J. S., Wright, C. T., Hess, J. R. & Kenney, K. L. (2011). A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application. *Biofuels, Bioproducts and Biorefining*, 5(6), 683-707.
- Tumuluru, J.S. & Yancey, N. (2018). Conventional and advanced mechanical preprocessing methods for biomass: Performance quality attributes and cost analysis. In *Biomass Preprocessing and Pretreatments for Production of Biofuels*; Tumuluru, J.S., Ed.; CRC Press: Boca Raton, FL, USA, 2018.
- Tumuluru, J.S. (2022). Systems and Methods of Forming Densified Biomass, US 2016/0002554 A1. United States Patent and Trademark Office, Alexandria, VA (2022).
- Tumuluru, J.S. (2016). Specific energy consumption and quality of wood pellets produced using high moisture lodgepole pine grind in a flat die pellet mill. *Chemical Engineering Research and Design*, 110, 82–97.
- Tumuluru, J.S., Frodeson, S., Mohammadi, A. & Venkatesh, G. (2024). Thermal Pretreatment Technologies for Moisture Removal and Upgrading the Biomass Quality. In: Bisaria, V. (eds) *Handbook of Biorefinery Research and Technology*. Springer, Dordrecht (https://doi.org/10.1007/978-94-007-6724-9_49-1).
- Tumuluru, J.S., Lim, C.J., Bi, X.T., Kuang, X., Melin, S., Yazdanpanah, F., Sokhansanj, S. 2015. Analysis on Storage Off-Gas Emissions from Woody, Herbaceous, and Torrefied Biomass. *Energies*, 8, 1745-1759.

US Department of Agriculture disclaimer

The findings and conclusions in this publication are those of the author(s) and should not be construed to represent any official USDA or US Government determination or policy. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the US Department of Agriculture. USDA is an equal opportunity provider and employer.