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Chapter 15

Biomass Blending and Densification: Impacts on Feedstock Supply and Biochemical Conversion Performance

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Additional information is available at the end of the chapter

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Abstract

The success of lignocellulosic biofuels and biochemical industries depends on an economic and reliable supply of high-quality biomass. However, research and development efforts have been historically focused on the utilization of agriculturally derived cellulosic feedstocks, without considerations of their low energy density, high variations in compositions and potential supply risks in terms of availability and affordability. This chapter demonstrated a strategy of feedstock blending and densification to address the supply chain challenges. Blending takes advantage of low-cost feedstock to avoid the prohibitive costs incurred through reliance on a single feedstock resource, while densification produces feedstocks with increased bulk density and desirable feed handling properties, as well as reduced transportation cost. We also review recent research on the blending and densification dealing with various types of feedstocks with a focus on the impacts of these preprocessing steps on biochemical conversion, that is, various thermochemical pretreatment chemistries and enzymatic hydrolysis, into fermentable sugars for biofuel production.

Keywords: blending, densification, conversion performance, advanced feedstock supply system, preprocessing

1. Introduction

Global demands for energy, finite petroleum reserves, and growing concerns over climate change have prompted considerable interest in lignocellulosic biomass as a sustainable alternative to fossil-derived sources for the production of transportation fuels. The Renewable

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Fuel Standard (RFS2) [1] mandates the use of 36 billion gallons of renewable fuels by 2022 under the U.S. Energy Independence and Security Act (EISA) of 2007 [2]. Biomass availability and quantity pose significant barriers to the realization of large-scale production of lignocellulose-derived biofuels. The U.S. Department of Energy's (DOE) 2016 Billion Ton Report has projected the potential for more than one billion tons of biomass in the form of agricultural, forestry, waste, and algal materials capable of displacing approximately 30% of U.S. petroleum consumption without adverse environmental effects or negative impacts to production of food and agricultural products [3].

The conversion of biomass into affordable bio-based fuels and chemicals aims to displace all of the products currently made from a barrel of oil. Research and development efforts focused on the production of bio-derived hydrocarbon fuels and products seek to mobilize the bioeconomy in order to diversify energy resources that enable energy production. However, development of biomass as a sustainable energy resource for fuels and chemicals will require advances aimed at solving logistical challenges to ensure a cost-effective and consistent feedstock supply to the biorefinery [4–7]. Efficient utilization of the available resources for biofuels production requires considerations of supply chain cost, feedstock quality and conversion performance that dictates overall process economics. Logistical operations like harvest, collection, preprocessing, storage, and transportation have a significant impact on biomass availability and feedstock cost and quality [6, 8]. The large-scale deployment of lignocellulosic biomass for energy production has been severely limited by the high cost associated with the feedstock supply chain and technology barriers in conversion to fuel [8–10].

Initial development of the biofuels industry has centered around high-productive, single-resource areas that rely on sufficient quantity to enable selection and sourcing of suitable materials for conversion processes. However, as the bioeconomy grows and production moves away from highly productive, resource-rich areas, the impact of the spatial and temporal variability inherent to biomass feedstocks [6] cannot be managed solely by passive means in order to meet requirements for quality and quantity. The expansion of the industry will necessitate the adoption of "advanced" concepts within the supply system in order to meet cost, quality, and quantity requirements.

In addition, the "conventional system" currently employed by the cellulosic biofuel industry relies on a vertically integrated feedstock supply system where a single biomass feedstock is procured through contracts with local farmers, harvested and stored locally, and delivered in a low-density, baled format to the conversion facility [7]. This system has been demonstrated to work in high-yield regions, such as the U.S. Corn Belt; however, recent analyses have shown that conventional systems fail to meet feedstock cost targets outside of highly productive regions [11]. Realization of large-scale production of lignocellulosic biofuels will require modification to the current system in order to enable a consistent, cost-effective, and continuous supply of biomass to the biorefinery [10]. In comparison, the advanced feedstock supply system (AFSS) employs a wide range of preprocessing techniques, such as feedstock blending and densification in distributed biomass depots, and shows great promise for enabling improvements in handling and quality, consistency and uniformity, facilitating access to resources, and stability in storage [4, 7, 12, 13].

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Biorefineries that rely upon a single feedstock to meet tonnage requirements are vulnerable to significant risks, in terms of both availability and affordability. Diversification of biomass supply has the potential to reduce risk [7], in some cases by as much as 80% [14], while enabling the lowest delivery cost [15]. Achieving a continuous, year-round supply of a single biomass resource is unlikely given the seasonal availability of most agricultural crops. Furthermore, climate change poses an inevitable risk to biomass supply systems for a developing bioenergy industry. Langholtz et al. [16] highlight the risk of extreme weather events to the bioenergy supply chain that are certain to cause reductions in feedstock production and increased price for agricultural commodities and biofuels. Other work has shown that drought has a significant, negative impact on biomass quality, in addition to biomass production yields [17]. Recent studies suggest a blended feedstock strategy to enable supply chain resilience may provide a solution to reliance on a single biomass resource [10, 18].

Low-density biomass feedstocks also pose a significant challenge to supply chain operations that translate to difficulties in storage, transportation, handling, and feeding [19], which hinder the large-scale use of biomass for biofuel production. Large volumes of low-density feedstocks require more resources for transportation and shipping. The size of the transportation resources needed to reach the 2050 target of 50% reduction of greenhouse gas via biofuels, biopower, and bioproducts exceeds the resources used to move the 2010 world grain and oil seed resources by 6- to 10-fold [20]. Densification processes, such as pelletization would increase the bulk and energy density of raw biomass, improve stability during storage and handling, create flowable feedstocks that are compatible with existing handling systems, and improve transport efficiency and cost [19].

The use of blended and densified feedstocks in conversion pathways instead of conventionally ground biomass from a single source addresses several challenges in the current biomass supply chain, including availability, transportation, storage, cost, quality, and supply variability [7, 19, 21–23]. This chapter provides a glimpse into the potential for preprocessing options, for example, blending and densification, to provide benefits to both biomass cost and conversion.

2. Addressing feedstock supply challenges

2.1. Feedstock blending strategy

A promising strategy to reduce supply risk is to blend different biomass feedstocks. Blending has been used by many industries (e.g., coal and animal feed) to affect the quality of the feedstock [24]. In the coal industry, different grades of coal are blended in order to meet emission targets and minimize ash production during power generation [25–27]. In the animal feed industry, a variety of feedstocks are blended to meet the desired nutritional requirements for a specific target animal [28]. Similarly, the concept of blending can be extended to the biofuel and bioproducts industry.

Formulating a designed feedstock through blending and other preprocessing methods allows low-cost and typically low-quality biomass to be blended with biomass of higher cost and typi-

cally higher quality to achieve the specifications required at the in-feed of a conversion facility (note that different conversion processes may require different specifications, and the cost required to meet those specifications will vary). The use of low-cost biomass allows the supply chain to implement additional preprocessing technologies that actively control feedstock quality, while also bringing more biomass into the system. This analysis and design approach is referred to as the "least-cost formulation" strategy [29]. In addition, recent work has shown that blended biomass feedstocks demonstrate improved flowability behavior [30], suggesting the potential for blending to extend benefits from the supply chain to feeding systems at the refinery.

The farmgate price is used to describe the economic availability of biomass resources and includes the cost of production and harvest [3]. **Figures 1** and **2** represent the cost of corn stover as a function of availability by state or region; these figures illustrate the increase in farmgate price with increasing demand. By blending feedstocks, the biorefinery can take advantage of the lower end of each supply curve to reduce cost. For example, **Figure 3** shows supply curves for switchgrass and corn stover from a 12-county region in northwestern Kansas, approximately 90 miles by 120 miles in size. In this region, only 700,000 tons per year of switchgrass (red curve) are available at $50/ton which could not support a biorefinery (capacity of ≥800,000 tons per year). There is sufficient corn stover to supply 1.6 million tons but at a farmgate price of $58/dry ton (blue curve). Thus, the strategy of combining the two feedstocks (green curve) shows that 1.6 million tons could be supplied to a biorefinery for a lower farmgate price of $48/dry ton.

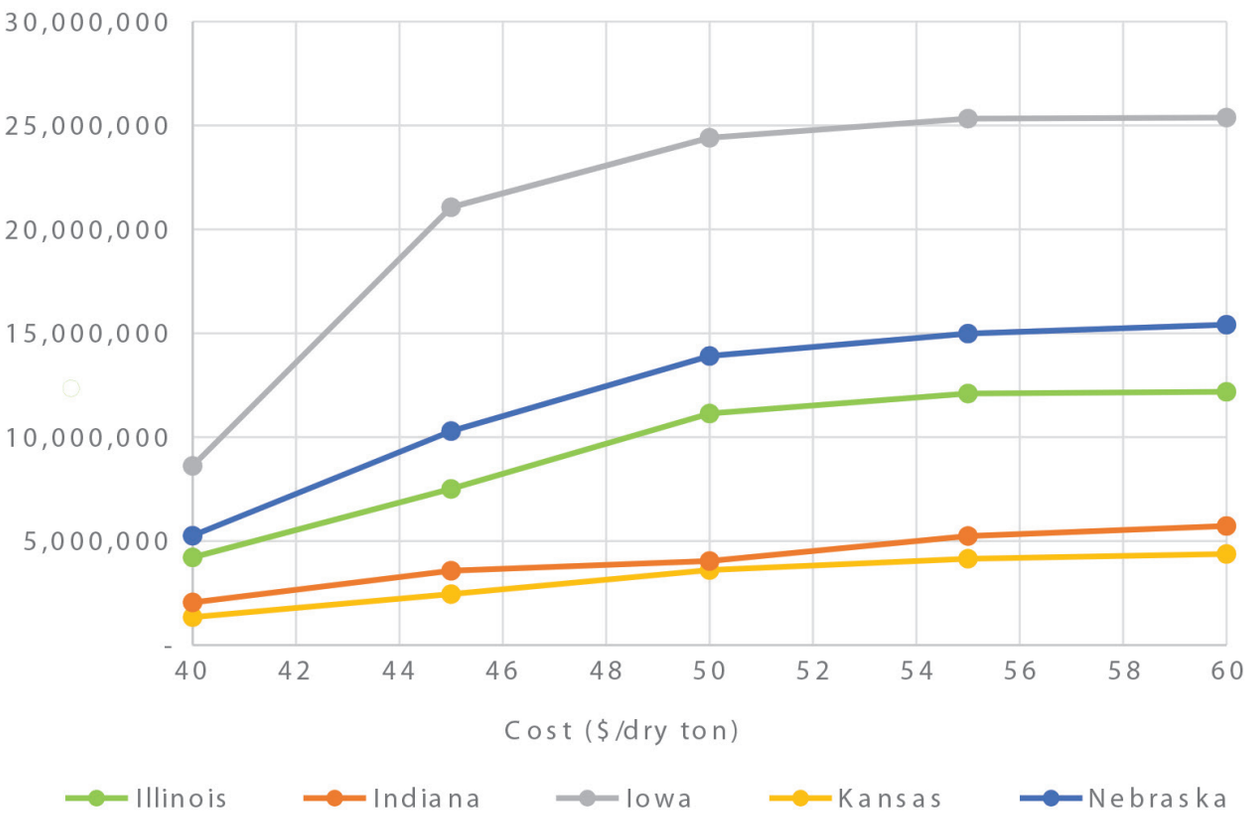


Figure 1. Corn stover availability by state as a function of farmgate price [33]. Availability and cost data assume base case corn stover yields for 2015. The data for each state is the sum of available corn stover for each county at a given farm gate price.

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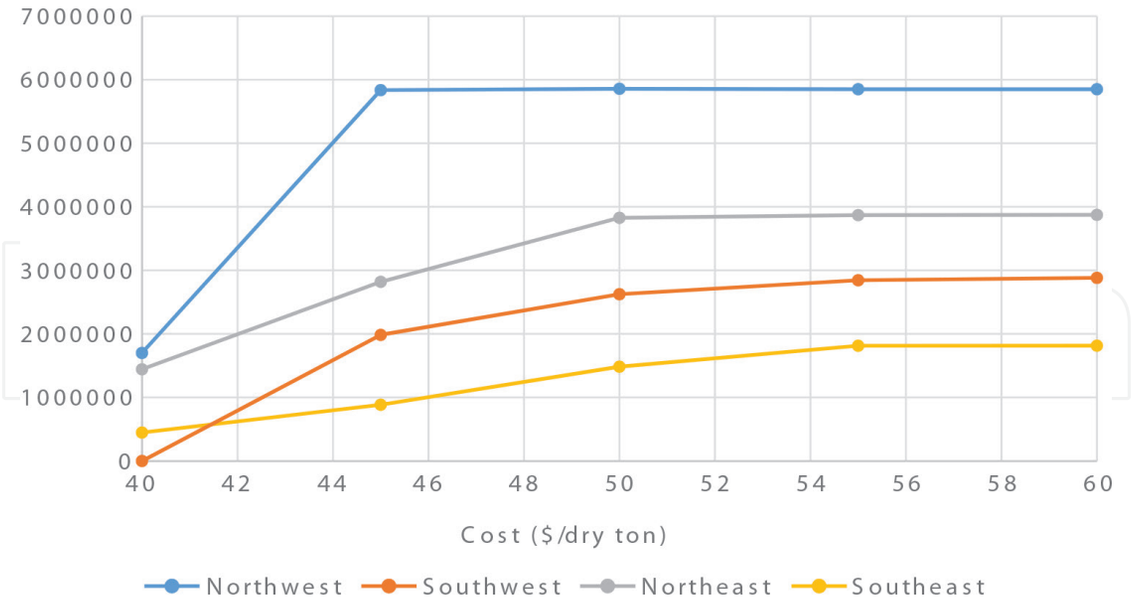


Figure 2. Feedstock supply curves for various locations in Iowa [33]. Availability and cost assume base case corn stover yields for 2015 for 61 counties in Iowa.

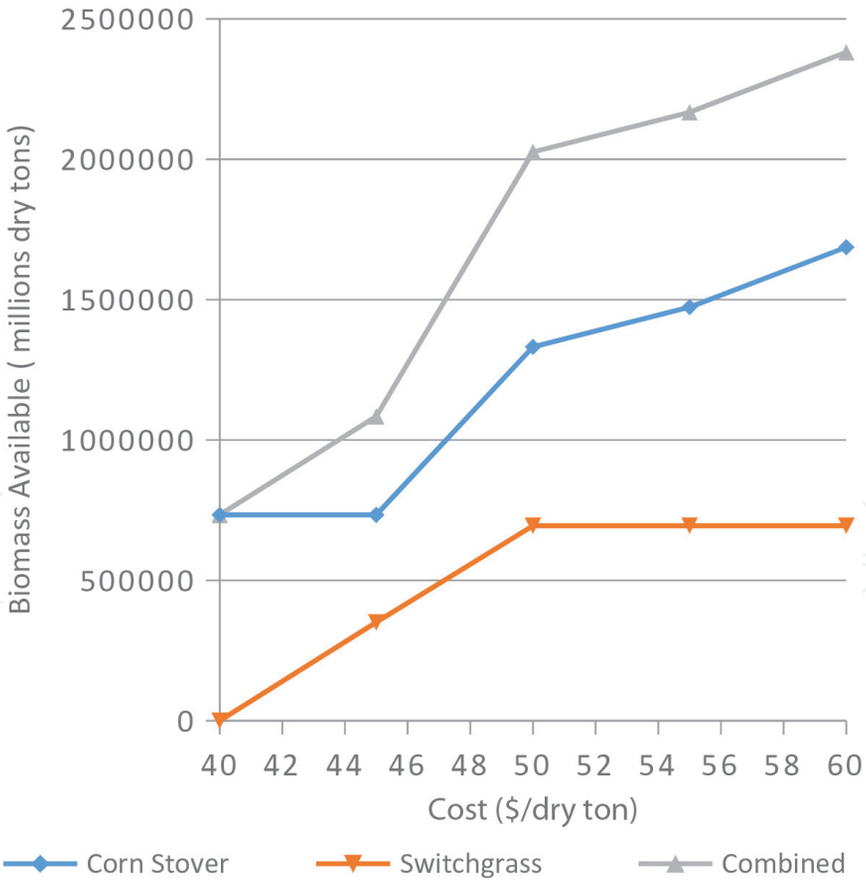


Figure 3. Biomass availability in northwestern Kansas as a function of farmgate price; prices and quantities shown are for 2015 and assume base case yields [34]. Supply curves illustrate biomass availability as a function of cost for a 12-county region in northwestern Kansas, with an approximate area of 90 miles × 120 miles. Curves are shown for corn stover (blue), switchgrass (red), and combined for a blended supply of corn stover and switchgrass (green).

Feedstock blending allows a biorefinery to utilize less of a single and expensive biomass type by collecting a variety of biomass (e.g., corn stover, switchgrass, sorghum, yard waste) and effectively moving down the cost versus supply curve and paying a lower average price for each feedstock. This does not change the supply versus cost curves for each resource; instead, it describes a system where purchasers are using a combination of least-cost resources and blending them to meet feedstock specifications for a subsequent biomass conversion process [29]. Costs may be further reduced by contraction of the draw radius for material collection, which reduces transportation cost. Feedstock formulation enabled through blending and other preprocessing strategies allows low-cost, low-quality biomass to be blended with higher cost and higher quality to achieve the in-feed specifications at the conversion facility. Blending feedstocks of differing quality results in a feedstock that has properties representative of the proportions of the materials that were blended together. Final price and quality are basically a weighted average of the price and quality of the components. It is important to realize a balance must be maintained and cost benefits may be not be linearly related to quality impacts. For many feedstock blends, there is likely a threshold quality level that cannot be surpassed to realize equal economic benefit. Biomass quality is a key consideration when analyzing biomass cost and availability. In combination with densification, wider sourcing areas can be tapped (including resources that are considered stranded using conventional supply systems).

Combining different biomass resources into the supply system also creates cost benefits by reducing overall grower payments [12]. The blended feedstock strategy relies on the availability of multiple feedstock resources that can be blended in an economical supply radius [31], which, in turn, decreases grower payment by reducing the required amount of any single biomass resource. In this manner, blending has the potential to expand the regionally available, biomass resource pool to include feedstocks of marginal quality at lower cost. In addition, a blended strategy offers the potential for feedstock quality upgrades and reduced variability [6, 21]. Blending high-quality feedstocks with low-cost, low-quality feedstocks is a strategy that can be used to meet quality specifications [21] at the biorefinery, in addition to achieving volume and cost targets in the supply chain [32]. An analysis by Maung and colleagues [18] has shown that a multi-crop cellulosic feedstock strategy lowers transportation costs compared to reliance on a single resource. Additionally, sourcing multiple feedstocks for cellulosic biofuel production mitigates supply risks associated with policies that govern crop residue removal. Further, Maung et al. suggest that a multi-feedstock strategy enhances understanding of the links between environmental policy, economies of density, economics of geography, transportation, risk and diversification in the biomass feedstock supply chain.

2.2. Densification

Reducing transportation costs while producing feedstocks with desirable (and consistent) physical properties such as increased bulk density and enhanced handling and processing characteristics requires densification of low-bulk density biomass. Commodity production for renewable fuels and chemicals requires large-scale biomass resources managed through AFSS and distributed biomass depots. These depots can provide feedstock stability, size reduction, and managed moisture [20]. Distributed biomass depots can reduce transportation and shipping costs

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and improve feedstock stability and consistency by employing strategies such as size reduction, moisture management, blending, and densification. This allows greater access to stranded feedstocks and can reduce grower payment through feedstock blending [4, 11, 35]. Reducing transportation costs while producing feedstocks with desirable (and consistent) physical properties such as increased bulk density and enhanced handling and processing characteristics requires densification of low-bulk density biomass.

Pelleted biomass is produced from raw, ground material that is conditioned with heat and/or moisture, compacted, and extruded through a die [2, 3]. The economics and physical properties of densified biomass formats produced from agricultural residues have been explored in several studies [36–39]. Pelleting of biomass can increase unit density of raw biomass resources by as much as 10-fold [19], resulting in a flowable and durable product that is compatible with existing biomass supply system infrastructure. It has been shown that activation of the natural binders in biomass, such as lignin, through combined moisture and temperature effects during the process of densification is key to the development of particle-particle bonding that is required for durability [9]. The extent of lignification contributes significantly to biomass recalcitrance [4], and lignin alteration during the process of densification may impact biomass reactivity to pretreatment and enzymatic hydrolysis [12].

Currently, there are many types of densification systems available: pellet mills, piston and roller presses, tabletizers, and extruders [19]. Pelleting of biomass can increase unit density of raw biomass resources by as much as 10-fold [1], producing a uniform, durable product with free-flowing characteristics that may be more compatible with biorefinery operations. The economics and physical properties of densified biomass formats produced from agricultural residues have been explored in several studies [2, 9–11]. Industrial pelleting has developed into a well-established process using wood and wood chips. Global pellet demand has reached 23-million metric tons [40].

3. Impact of blending and densification on pretreatment processes in biochemical conversion pathways

Thermochemical pretreatment processes are used in biochemical conversion pathways to facilitate enzymatic access to cellulose and enable conversion of complex carbohydrate polymers into fermentable sugars. These promising processes include ammonia fiber expansion (AFEX), dilute acid, alkaline and ionic liquid (IL) pretreatment technologies. Specifically, AFEX is a physicochemical pretreatment process performed under high pressure (200–400 psi) and moderate temperature (80–150°C) with concentrated ammonia for a brief residence time (5–30 min) before pressure release [41]. AFEX pretreatment facilitates enzymatic access to cellulose by breaking down the cellulose crystalline structure and depolymerizing the lignin. Dilute-acid (DA) pretreatment relies on the combined effect of dilute sulfuric acid (0.25–2 wt.%), temperature (140–200°C), and time (seconds to minutes) to solubilize hemicellulose and improve enzymatic accessibility to cellulose [42, 43]. Alkaline pretreatment technologies focus on lignin solubilization and deacetylation under relative mild conditions (60–180°C) with NaOH or ammonium hydroxide (i.e., soaking in aqueous ammonia,

namely SAA) as catalyst [44–46]. Recently, ILs are receiving significant attention as a class of novel environmental benign "green solvents" to dissolve and disrupt the biomass cell wall, reduce cellulose crystallinity and lignin content, and increase the porosity and surface area for enhanced enzymatic digestibility [26, 47–52]. In addition, this pretreatment technique shows great capability of fractionating wide range of feedstocks [50, 52, 53].

Although significant efforts have been focused on pretreatment of single lignocellulosic biomass in loose and ground format, recently researchers started to look into the application of biomass blending and densification for biochemical conversion into fermentable sugars. The details of biomass blending and quality improvement, characteristics of various densification formats of diverse feedstock types, and their impacts on conversion performance are discussed below.

3.1. Impact of biomass blending

Feedstock blending is one approach offering promising solution to overcome current challenges on biomass supply such as significant compositional variations [21, 22]. Therefore, it is imperative to develop conversion technologies that can process blended biomass feedstocks with minimal negative impact in terms of overall performance of the relevant biochemical pathway unit operations: pretreatment, fermentable sugar production, fermentation, and fuel titers.

Ionic liquid (IL) pretreatment has shown uniqueness in efficiently handling wide range of feedstocks; thus, this technology was investigated on the feasibility to process mixed feedstocks. It was firstly demonstrated in a US patent that the two or more feedstocks, including softwood, hardwood, grass, agricultural residues, and byproducts, can be combined for IL pretreatment with equivalent sugar conversion in comparison with single feedstocks [54]. Shi et al. evaluated the efficiency of feedstock blending along with the densification coupled with IL pretreatment to address the issues of feedstock diversity and compositional variations [55]. The IL 1-ethyl-3-methylimmidizolium acetate can process mixtures of pine, eucalyptus, switchgrass, and corn stover (in 1:1:1:1 ratios) and result in fast saccharification by reaching 90% digestibility within 24 h, which is comparable to any single feedstock type among the four starting biomass materials [52, 55]. A continuation study was further performed to investigate the IL pretreatment of the same mixture of four biomass in both flour and pellet formats, in comparison with dilute acid (DA) and soaking in aqueous ammonia (SAA) pretreatment methods, for simultaneous saccharification and fermentation into advanced biofuel isopentenol [26]. Their results show significant variations on the chemical composition, crystallinity, and enzymatic digestibility of the pretreated feedstock across the three different pretreatment technologies studied. IL pretreatment liberated the highest sugar titers from mixed biomass either in flour or pellets and is capable of handling mixed feedstocks with equal efficiency, and thus outperformed DA and SAA pretreatment methods which are more effective in pretreating herbaceous biomass feedstock and less effective in woody biomass for the mixed feedstock utilization. The high sugar production from IL process in turn led to the highest isopentenol titers in fermentation as compared to DA and SAA pretreatments.

While these three studies focused on the blends of various feedstock types that are agriculturally derived, researchers also looked into the utilization of the municipal solid waste as blending

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agent with lignocellulose to provide lower cost of biorefinery feedstock inputs [51]. The MSW/corn stover blends (ratio varying from 1:1 to 1:9 on the dry weight basis) went through two types of IL pretreatment for sugar conversion, one is pretreatment by IL 1-ethyl-3-methylimidazolium acetate followed by enzymatic hydrolysis, and another is enzyme-free acidolysis in IL 1-ethyl-3-methylimidazolium chloride with addition of mineral acid. Both processes show promising sugar conversion with glucose yield over 80% and xylose yield over 75%, suggesting the great potential to use MSW for biofuel production while maintaining performance and lowering cost.

Since the data from these four studies of biomass blends were obtained at low solid loading and milliliter level of operations, which cannot be directly transferred to industrially relevant scales, Li et al. performed the process scale-up and integration of IL1-ethyl-3-methylimidazolium acetate pretreatment on herbaceous (switchgrass) and woody (eucalyptus) blends (1:1 ratio) by 30-fold at 10% solid loading [50]. In comparison with single feedstocks, this biomass blend recovered similar yields of glucan, xylan, and lignin as switchgrass and eucalyptus at 6-L scale operation. The pretreated mixed feedstock was further enzymetically hydrolyzed at 2-L scale with 96% sugar yield [50, 56]. Additionally, the same group also investigated the scale-up of IL acidolysis using 1-ethyl-3-methylimidazolium chloride and mineral acid on MSW/corn stover blends and obtained sugar conversion yields that are comparable to small-scale studies [51, 53, 57]. These results indicate that mixed feedstocks, either agriculturally derived or MSW blended, are viable and valuable resources to consider when assessing biomass availability and affordability demands of the biorefineries. These initial scale-up evaluations demonstrate that IL-based pretreatment is feedstock agnostic, and there is no fundamental issues in terms of performance associated with the larger operations. This early-stage, 6-L scale-up process development integrates the unit operations of pretreatment, homogenization, continuous washing/separation, and product recovery for simplified feedstock handling, reduced water consumption and mitigation of IL inhibition, all of which can be further connected with downstream microbial fermentation for advanced biofuel production.

A few studies have examined the impact of blended or mixed biomass feedstocks on sugar yields from biochemical conversion using other pretreatment technologies. Karki et al. [58] reported on the enzymatic hydrolysis of mixtures of switchgrass and tall wheatgrass following dilute-acid and aqueous ammonia pretreatments. Switchgrass and tall wheatgrass were similar in composition before and after dilute-acid pretreatment, although tall wheatgrass had significantly higher glucose yields from enzymatic hydrolysis. Mixtures of the two species produced glucose yields that were higher than switchgrass and lower than tall wheatgrass following dilute-acid pretreatment and enzymatic hydrolysis. This study also demonstrated hydrolysis yields for mixtures could be predicted based on results of the individual components.

Brodeur-Campbell et al. [59] reported on the effects of biomass mixtures on sugar recovery from combined dilute-acid pretreatment and enzymatic hydrolysis. Aspen, a hardwood species that is suitable for efficient biochemical processing, was chosen as a model species in this study. Balsam, representing a high-lignin, softwood species, and switchgrass, a herbaceous energy crop with high ash, were chosen for comparative studies using 1:1 mixtures of

aspen:balsam and aspen:switchgrass. No synergistic or antagonistic effects were identified in this study for three different pretreatment severities and three enzyme loadings examined. Again, total sugar recoveries for mixtures could be predicted by linear interpolation (±4%) from sugar yields of the pure biomass species. Similarly, Wolfrum et al. examined the effect of blending combined with densification on sugar yields from blends of corn stover, switchgrass, and *Miscanthus* biomass feedstocks [60, 61]; results showed the pelleting had a slightly positive, although not significant effect on total sugar yield. As in the previous studies, sugar yields could be predicted with reasonable accuracy from knowledge of the pure biomass feedstocks.

These studies demonstrate the efficient conversion of blended feedstocks to fermentable sugars and highlight the great potential for blending to expand the available resources for biofuel production. Biomass blending strategy certainly provides equivalent conversion performance as compared with single feedstock, in addition to its economic benefits toward the future development.

3.2. Impact of biomass densification

Lignocellulosic biomass with low bulk and energy density requires relatively high energy to transport, store, and distribute the feedstock from the field to the biorefinery gate for conversion, and the loose ground materials often pose problems of material feeding and handling in the reactors. Biomass densification typically involves exposing the biomass to elevated pressures and temperatures to remove excess water and compress the biomass. This process acts as a mild thermochemical pretreatment and can also impact the composition and structure of the biomass [55]. Several densification forms have been demonstrated recently, and this section reviews and compares the impact of densification on various thermochemical pretreatment.

3.2.1. Pellets

Recently, a growing body of literature has assessed the impact of pelletizing herbaceous and woody materials on the bioconversion process when combined various pretreatment technologies. Pelleted biomass is produced from raw, ground material that is conditioned with heat and/or moisture, compacted, and extruded through a die [2, 3]. It has been shown that activation of the natural binders in biomass, such as lignin, through combined moisture and temperature effects during the process of densification is key to the development of particle-particle bonding that is required for durability [9]. The extent of lignification contributes significantly to biomass recalcitrance [4], and lignin alteration during the process of densification may impact biomass reactivity to pretreatment and enzymatic hydrolysis [12].

Published reports evaluating the impact of pelletization on the bioconversion of corn stover, sorghum, wheat straw, big bluestem grasses, softwood, and switchgrass have shown positive trends using lower severity alkaline pretreatment. Similar or slightly higher sugar release and ethanol yield were observed in the pelleted format when compared to the nonpelleted format after pretreatment and enzymatic hydrolysis. Guragain et al. [62] evaluated the effect of alkaline pretreatment on sugar release and ethanol production in pelleted and nonpelleted wheat straw, corn stover, big bluestem, and sorghum stalk; mass recovery after alkali pretreatment increased by 14, 11, 2, and 5%, respectively, compared to nonpelleted biomass. Volumetric

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sugar production increased for all feedstocks except sorghum, although final sugar yields were not significantly different between the pelleted and non-pelleted biomass. Nahar and Pryor [63] reported that combining pelleting and pretreatment with SAA treatment reduced cellulase loading to achieve 90% glucose yield at 10 FPU per g glucan in switchgrass. Pelleting the switchgrass did not affect the feedstock composition compared to the non-pelleted switchgrass. Hoover et al. [64] evaluated the effect of physical properties resulting from pelleting AFEX-pretreated corn stover. Comparing grind size, die speed, and preheating on pellet properties on the sugar release after enzymatic hydrolysis showed the following: Die speed had no effect on sugar yield, while a larger grind size (4 mm vs. 6 mm) had a similar or lower effect on sugar yields after enzymatic hydrolysis. Overall, pelleting AFEX-treated biomass increased or had no effect on sugar yields at low or high ammonia loadings. Bals et al. [65] tested the susceptibility of AFEX-treated, corn stover pellets to enzymatic hydrolysis at high solids loading (18–36%). Pelletization slightly increased the initial rate of hydrolysis relative to raw biomass, enabled mixing, and resulted in higher glucose yields at 18% solids loading relative to unpelletized biomass (68% vs. 61%). Similarly, Rijal et al. [66] demonstrated that DA-treated switchgrass did not impact glucose yield in the finer ground, and pelleted materials compared to the native material. However, glucose yields from aqueous ammonia pretreatment, followed by enzymatic hydrolysis, were higher for both powder and pelleted materials compared to the native material. Glucose yield for the DA- and SAA-treated and pelleted switchgrass was 98 and 79%, respectively.

Theerarattananoon et al. [67] evaluated the impact of pelleting conditions on sugar release and chemical composition of corn stover, wheat straw, sorghum stalk, and big bluestem grass. Dilute-acid pretreatment and subsequent enzymatic hydrolysis increased glucan content in the pretreated solids compared to the nonpelleted companion feedstock for corn stover, wheat straw, and big bluestem prairie grass. Glucan content in the pretreated pelleted sorghum stalks was slightly less than nonpelleted sorghum stalks. Enzymatic hydrolysis results suggested that pelleting increased cellulose yield for all feedstocks. While wheat straw had the highest cellulose yield (94.1%), Ray et al. [68] evaluated the impact of densification on the bioconversion of corn stover, ground and pelleted format. The low solids dilute-acid pretreatment resulted in higher theoretical ethanol yields from the pelleted versus the non-pelleted format of 84 and 69%, respectively. Pelleted and ground corn stover was pretreated at higher solids loading at multiple pretreatment severities and showed slightly increased reactivity across three of the five severities tested.

Similar to other pretreatment technologies, conversion of biomass feedstocks with low energy and bulk density using ILs is not an economic process. To address this issue, Shi et al. investigated and compared the IL pretreatment of switchgrass, lodgepole pine, corn stover, and eucalyptus in both flour and densified pellet formats with 1-ethyl-3-methylimmidizolium acetate at 160°C and 10% solid loading for 3 h [55]. There was no significant difference between the physio-chemical properties, that is, composition and cellulose crystallinity, of the pretreated flour and pellets. The subsequent enzymatic digestibility results show that sugar yields from both formats reach 90% conversion within 24 h, suggesting densifying a wide range of feedstocks may be a competitive solution with no significant adverse impacts, provided that they are coupled with the appropriate conversion technology. Although significant improvements in

terms of IL cost and recycling need to be resolved before this technology is commercially viable, biomass densification certainly provides the economic benefits toward the future development.

3.2.2. ComPAKo briquettes

Additional studies have been performed quantifying ethanol yields from densified AFEX-pretreated corn stover, switchgrass, and prairie cordgrass. Rijal et al. [69] studied the effect of initial particle size (2, 4, 8 mm) and densification on ethanol production. They employed a novel densification method, ComPAKo that uses a gear, mesh system to produce compacted biomass briquettes (1 inch × 0.5 inch × 4 inch). The ComPAKo equipment operates at lower temperatures (30–60°C) and pressures, lowering energy costs. Also, the capital investment for ComPAKo is less than half that of a pellet mill. The bulk density of the briquettes ranged between 380 and 460 kg/m^3 with moisture content of 11–15%. The AFEX-pretreated biomass was used for both simultaneous saccharification fermentation (SSF) at 4% glucan loading and separate hydrolysis with fermentation (SHF) at 1% glucan loading with an enzyme loading of 15 FPU and 64 CBU/g of glucan for hydrolysis. Results demonstrated that 2-mm densified corn stover briquettes yielded approximately 5% higher ethanol than 8-mm densified material. They also showed that grinding the densified 8-mm briquettes to 2 mm prior to SSF studies did not result in significant ethanol yield differences, but the 2-mm densified corn stover showed 4% higher yield than post-grinding the 8-mm briquettes prior to hydrolysis. The ethanol yields from the SSF did not significantly differ for the AFEX-treated corn stover or switchgrass when compared to the densified AFEX-treated material, but they noted a negative impact for the prairie cordgrass densified material by 16%. This was attributed to the observation that densified AFEX-treated prairie cordgrass was stronger and did not break apart during mixing and hydrolysis. Upon grinding of the AFEX-treated densified prairie cordgrass, the ethanol yields were 35% less than with the nondensified material, indicating that prairie cordgrass densification is not beneficial. The negative impacts of densification on AFEX-treated prairie cordgrass may be attributed to amount or structure of lignin in this feedstock. Sugar yields during SHF were not impacted for the corn stover or switchgrass densified material, but they were significantly diminished for prairie cordgrass. However, when comparing SHF ethanol yields, switchgrass densified material gave significantly lower yields, while yields from densified corn stover were only slightly higher, but the densified prairie cordgrass produced higher yields than either corn stover or switchgrass. The results support AFEX as an effective pretreatment technology for ComPAKo densification processes, thus reducing the need for additional particle size reduction for effective hydrolysis. These technologies however will produce different sugar and ethanol yields dependent on feedstock choice and subsequent hydrolysis and fermentation. AFEX-treated densified corn stover yielded the better quality briquettes of the three biomass types tested in the AFEX-treated, ComPAKo processes.

Biersbach et al. [70] also studied ethanol yields from briquettes of AFEX-treated corn stover, switchgrass, and prairie cordgrass and assessed the impact enzyme loading has during SSF and SHF, and they tested storage of these densified materials. They used the ComPAKo method to produce briquettes of 1–2 cm with a bulk density range between 380 and 460 kg/m^3 and moisture content of 11–15%. Ethanol yield was improved for all AFEX-pretreated biomass tested regardless of enzyme dose or fermentation regimen (SSF or SHF). They found that ComPAKo densified AFEX-treated biomass did not consistently have an impact on ethanol yields in most

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of the conditions they tested, but in three of the corn stover tested conditions, densification increased ethanol yields up to 13%. For experiments using switchgrass and prairie cordgrass densified material, the densification caused 7 and 22% reduction in ethanol yields, respectively. They concluded that the ethanol yield differences of the various feedstocks could be attributed to the glucan content and pretreatment efficiency. They also found that the higher enzyme dose (15 FPU Spezyme CP, 64 CBU Novozyme 188) during enzymatic hydrolysis generally increased ethanol yields in the range of 18–317% for SHF and 28–62.5% for SSF, dependent on the feedstock. When the AFEX-treated densified briquettes were stored for 6 months, there was an increase in ethanol yield of 12–17%, with the exception of the prairie cordgrass which gave a 55% reduction in ethanol yield when SHF was performed, but not with SSF.

3.2.3. Extrusion pelleting

Extrusion pelleting is another densification technology that Sundaram and Muthukumarappan [71] used to evaluate AFEX-pretreated corn stover, switchgrass, and prairie cordgrass. They tested the effects of various parameters during laboratory-scale single-screw extrusion pelleting and the impact of those parameters on pellet bulk density, hardness, and sugar recovery from enzymatic hydrolysis. The parameters tested included moisture content (5, 10, and 15%), hammer mill particle size (2, 4, and 8 mm), and extrusion barrel temperature (75, 100, and 125°C). In general, the bulk density of the AFEX-treated biomass particles decreased as the particle size increased, and the bulk density increased with increasing the moisture content. Similar to other studies, the AFEX-pretreated material increased the pellet bulk density for each feedstock (650.6 kg/m^3 for corn stover, 680.1 kg/m^3 for prairie cord grass, and 627.7 kg/m^3 for switchgrass) compared to untreated material (453.0, 463.2, and 433.9 kg/m^3, respectively). The moisture content significantly impacted pellet bulk density with higher moisture content causing an increase. However, particle size of AFEX-pretreated material had no impact on pellet bulk density, but it inversely affected the untreated pellets; likewise extrusion temperature did not significantly impact AFEX-pretreated pellet bulk density but did negatively impact the untreated material. Pellet hardness was also determined for AFEX-pretreated pellets of corn stover, switchgrass, and prairie cordgrass with maximum hardness values of 2342.8, 2424.3, and 1298.6 N for each feedstock, respectively. The hardness of the AFEX-treated pellets was not significantly different at different barrel temperatures, indicating that good quality pellets can be achieved at 75°C, thus reducing costs. Moisture content correlated with pellet hardness for treated and untreated materials which is typical for extrusion pelleting and in combination with moisture content, particle size impacted pellet hardness, with 2 and 4 mm particles yielding maximum hardness. The percent glucose released form AFEX-pretreated pellets ranged from 88.9 to 94.9% for corn stover, 90.1 to 94.9% for prairie cord grass, and 87.0 to 92.9% for switchgrass. These glucose yields were 1.6, 2.1 and 2.3 fold higher than those from untreated pellets, respectively and xylose yields increased 1.6, 1.4, and 2.0 fold for AFEX-treated pellets compared to untreated pellets, respectively. Neither glucose yields nor xylose yields were significantly impacted by the extrusion temperatures or the particle sizes tested during extrusion pelleting, again indicating a low temperature of 75°C can be used to achieve quality pellets for conversion. Finally, the results show the extrusion pelleting process can be performed at low temperatures and larger particle size without significantly impacting sugar yields, thus reducing pellet processing costs.

These key findings suggest that densification of biomass does not negatively affect its composition and downstream conversion and may actually increase bioconversion or perhaps reduce the requirements for a given conversion level. However, many of these evaluations involving herbaceous feedstocks were conducted under low-solids, non-mixed, and batch conditions, which make extrapolations to more process-relevant conditions difficult.

4. Summary

This book chapter evaluates the potential of preprocessing options, that is, blending and densification, for uniform, consistent, quality-controlled, and cost-effective feedstock development, and reviews their impacts on feedstock supply chain logistic and downstream conversion performance. The use of blended and densified feedstocks in conversion pathways instead of conventionally ground biomass from a single source addresses several challenges in the current biomass supply chain, including availability, transportation, storage, cost, quality, and supply variability. Review and summary of recent research further demonstrate that a biomass blending strategy provides an efficient way to meet quality and conversion performance specifications in comparison with the conversion of single feedstock. Densified formats can perform equivalent to non-densified formats in terms of sugar and ethanol biochemical conversion performance. Both blending and densification provide great promise to enable more cost-effective downstream processing.

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