

Energy Requirement for Lignocellulosic Feedstock Densifications in Relation to Particle Physical Properties, Preheating, and Binding Agents

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ABSTRACT: The low bulk density and low flowability of lignocellulosic biomass feedstock have been regarded widely as major barriers for a sustainable and efficient supply system. Densification of biomass is a viable option to increase the bulk (and inherent energy) density and flowability of feedstock, leading to improved efficiency of the supply system. The energy consumption of feedstock densification is one of the key variables that determines the efficiency of the feedstock supply. This paper investigates the energy consumption of herbaceous feedstock compression in relation to particle physical properties, preheating, and binding agents, such as steep water and thin stillage, both byproducts of corn ethanol production. The results indicate that the specific energy consumption for mini-bale densification was a function of the particle size, moisture content, and feedstock type. During pelletization, where all pellets were exposed to an identical maximum pressure, preheating temperature, particle size, and moisture content played a significant role in improving the energy efficiency and pellet density. Both binding agents increased the energy requirement for pelletization but yielded more durable pellets.

1. INTRODUCTION

The interest in producing energy from biomass has increased in recent years, owing to depleting fossil energy supplies, increasing concerns over energy security, oil price spikes, and climate change caused by carbon emissions.^{1–3} The European Commission Directive 2009/28/EC has set the goal of using a minimum of 10% sustainable biofuels within the transportation sector of every member state by 2020.⁴ The United States Department of Energy (DOE) is targeting the replacement of 30% of the U.S. petroleum consumption with biofuels (60 billion gallons) by 2030.³ The joint U.S. DOE and U.S. Department of Agriculture (USDA) released a technical report that investigates the feasibility of producing a billion tons of feedstock annually.³

The success of biofuel provision is highly dependent upon a cost-effective and sustainable supply of feedstock. The low efficiency of feedstock preprocessing and delivery is a major barrier to a sustainable energy production while limiting procurement of funding for startup biorefineries.^{5,6} Lignocellulosic feedstock is characterized by a low bulk density, low energy density, and low flowability, particularly for prairie-grass-type energy crops, agricultural residues, and wastes. These characteristics limit the efficiency of biomass preprocessing, handling, transportation, and storage. For instance, the transportation costs depend upon the feedstock densification level and represent between 13 and 28% of the production price of bioenergy.^{7–9} It is therefore imperative to investigate biomass densification to improve the feedstock supply conversion sector efficiency.^{10–12}

Lignocellulosic biomass end-users use feedstock in various forms: biomass pellets, briquettes, cubes, veneer, and even bales, which have been adopted for co-combustion with coal or

direct combustion for domestic heating, steam, and electricity generation.^{13–17} In recent years, biomass pellets, cubes, and briquettes have been widely used for biofuel thermochemical or hydrothermal conversion through torrefaction, using either pyrolysis or gasification followed by Fischer–Tropsch synthesis.^{14,15} Feedstock in pellet, briquette, cube, and veneer forms can be easily conveyed, allowing for control over energy release and CO₂ emission during combustion, torrefaction, and hydrothermal processes.^{13,18} Pellets and briquettes (or cubes) in a container or bag can also be transported and stored easily. In addition, compression and pelletization represent elementary processes in the production of the “uniform” and “advanced uniform” feedstock forms, which is aimed at the reduction of supply-chain costs and improvement of supply efficiencies.^{5,6}

In biomass feedstock rheology, densification comprises a complex interaction among pressure-induced forces, feedstock forms, physical properties, chemical composition, and moisture content.^{19–22} To produce pellets and briquettes, biomass feedstock is ground into 2–8 mm particles using size-reduction equipment.^{15,23} The particle size is a factor that affects the biomass compression and pelletization energy requirement.^{21,24,25} The main objectives in feedstock rheological compression research are the measurement of energy consumption and the influence of feedstock properties and binding agents on force-deformation behavior.

Biomass densification can be categorized as follows: (1) low-level compression, with the objective to contain the material with wiring, netting, or a container by increasing the density to

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a level that does not require decompression for subsequent treatment, and (2) high-level compression, with the objective to produce a self-contained material by increasing the density to a level that may require decompression for subsequent treatment. Low-level compression is mainly used for bulk-format or bale compression with a string or net wrapper, bag, container, or trailer equipment to hold the post-densification biomass.²⁶ High-level compression is mainly used for pellets, briquettes, cubes, and veneer.

The stress–strain behavior of biomass feedstock under compression has received ample attention in the literature.^{6,9,15,25,27} Numerous studies on force-deformation rheology and equipment design have been published for forage bale compression, as well as wood and prairie grass pelletization.^{16,24,28,29} However, the energy consumption–bulk density relationships vary as a function of crop species, feedstock form, and feedstock physical and chemical properties.^{19,22,28,29} A theoretical compression model was devised and found complicated while containing many unknown material property parameters.²⁹ Empirical exponential and power models were adopted to describe the relationship between energy consumption (or pressure) and volumetric deformation of biomass

$$E = ae^{bx}(P_x = ae^{bx}) \quad \text{or} \quad E = ax^b(P_x = ax^b) \quad (1)$$

where E in kJ kg^{-1} of dry matter (DM) is the cumulative specific energy consumption at position x during densification, P_x in Pa is the average pressure in the compression chamber at position x , x in m is the piston displacement during compression, and a and b are parameters.^{15,27,28} Few compression studies focus on the relationships between energy requirement, feedstock particle properties, preheating, and binding agents. Energy consumption of biomass densification plays an essential role in studying the efficiency of feedstock supply conversion systems. To fill this knowledge gap, the objective of this research was to comprehensively determine the energy consumption of biomass densification in relation to the particle size, feedstock temperature, moisture content, and role of binding agents.

2. MATERIALS AND METHODS

In this study, *Miscanthus* (*Miscanthus* × *giganteus*, Poaceae/Gramineae), switchgrass (*Panicum virgatum* L., Poaceae/Gramineae), and willow (*Salix babylonica*) were used as test materials. Corn stover was used as a reference feedstock in pelletization experiments. *Miscanthus* and switchgrass were planted at the Energy Farm of the University of Illinois at Urbana–Champaign in 2004 (latitude, 40.065799; longitude, −88.208599). The crop was harvested in the early spring of 2007.³⁰ *Miscanthus* and switchgrass bales with a size of $1.2 \times 1.2 \times 2.4$ m were stored for 1 year in a roofed open-air storage building at the Beef and Sheep Research Facility of the University of Illinois (latitude, 40.056112; longitude, −88.206735). Bales were chosen at random and broken up. Random samples from *Miscanthus* bales consisted of approximately 70–80% stem material and 20–30% sheath and leaf material. Switchgrass bales consisted of 55–70% stem material and 30–45% sheath and leaf material. Before milling, biomass samples were spread out in layers with a thickness of less than 15 cm on a laboratory floor and allowed to air-dry, following the National Renewable Energy Laboratory (NREL) analytical procedure. Three replicates of 20–25 g of biomass for each sample were allowed to dry for 24 h in an oven at 103 ± 3 °C to determine their moisture content, following the American Society of Agricultural Engineers (ASAE) S358.2 DEC1988 (R2008) standard for forage analysis. The material was considered dry when the moisture content was less than 10% and the change in weight was less than 1% in 24 h. Corn stover was

harvested at the South Farm of the University of Illinois during the month of October 2010. The material was manually chopped into 0.3–0.6 m long chunks and stored in a cold room at 0 °C for 4 months. Prior to grinding, the stover was dried at 49 °C for 72 h.

A total of 3 kg of unbaled *Miscanthus* (approximately 0.3–1.2 m long) and switchgrass (approximately 0.16–0.6 m long) was ground through 6.35 or 12.7 mm circular-opening screens using a commercial-scale chopping machine (David Bradley 5152W, Westinghouse Electric Corporation, Sears Roebuck and Co., Hoffman Estates, IL). These materials were further ground into finer particles using a knife mill (Retsch SM2000), which features milling screens with apertures ranging from 1 mm trapezoidal to 2, 4, 6, 8, and 10 mm square openings.²³ Corn stover was ground with the Retsch knife mill through a 6 mm aperture screen.

A willow (*S. babylonica*) tree trunk was harvested from a 30-year-old tree grown in a residential area of Champaign county, IL. The diameter at breast height of the tree was approximately 1.20 m. The biomass sample consisted of epidermis, cortex, bark fibers, phloem, xylem, and pith of the tree trunk but did not contain any branches, twigs, or leaves. Prior to size reduction, the tree trunk was cut into chunks with a size of $10\text{--}15 \times 10\text{--}15 \times 20\text{--}25$ cm using chain and band saws and further cut into a size of $0.6\text{--}5.8 \times 0.6\text{--}7.6 \times 0.5\text{--}2.5$ cm with a gas-powered wood chipper (Vermeer BC600, Eureka, IL). The wood chips were further ground with the Retsch knife mill. The particle size distribution and other properties of *Miscanthus*, switchgrass, and willow as used here can be found in a previous publication.²³ The energy consumption for biomass material preparation and size reduction were not accounted for in the results.

2.1. Experimental Design. A partial factorial experimental design was employed to investigate the energy consumption of mini-bale compression and pelletization. For mini-bale compression tests, the experimental factors were as follows: three energy crops, including *Miscanthus*, switchgrass, and willow; two moisture levels, i.e., air dry (7–10%) and 15%; and biomass forms comprising loose unground biomass with 7.5–25 cm long stems and particles ground through 1, 2, 4, 6, 8, 12.7 (or 10 mm for willow), 25.4, and 38.1 mm screens.²³ Each compression experiment was repeated 3 times, resulting in 85 mini-bale experiments.

The pelletization experimental factors were as follows: four energy crops, including *Miscanthus*, switchgrass, willow, and corn stover, two cylinders with plunger diameters of 12.7 and 25.4 mm filled with 5.0 and 1.5 g of biomass, respectively; six biomass forms comprising particles ground through 1, 2, 4, 6, 8, and 12.7 mm (or 10 mm for willow) sieves; three preheating temperatures at 22, 75, and 125 °C; two pressure levels applied being 47.4 and 189.5 MPa; and two binding agent levels (i.e., with or without binding agents). Each experiment was repeated 3 times, resulting in 689 pelletization experiments.

2.2. Experimental Procedures. **2.2.1. Mini-bale Compression and Pelletization.** For mini-bale compression experiments, the volume of the mini-bale chamber was $150 \times 150 \times 203$ mm, constructed from steel tubing with a wall thickness of 6.35 mm (Figure 1a). A 12.7 mm thick cap was constructed and welded to a socket that matched the cross-tube mounting style of the hydraulic cylinder. The mini-bale chamber was held in place laterally with four 15 mm tall plates protruding from the baseplate, allowing for easy cleanout of the compressed sample by separating the chamber from the baseplate. For the mini-bale compression experiments, the container was filled with up to 400–500 g samples. Subsequently, the material was compressed to a hydraulic fluid pressure of 5.5 MPa, which translated into 1.2 MPa pressure applied to the biomass.

For the pelletization experiments, two plunger/cylinder sizes were used with diameters of 12.7 and 25.4 mm (Figure 1b). Biomass samples weighing 1.5 and 5.0 g were fed into the cylinders.

2.2.2. Conditioning Moisture Content of Biomass Feedstock. For loose unground feedstock, first, the moisture content of the air-dried biomass was measured. Subsequently, to condition the material to a desired moisture content of 15%, the amount of water needed was calculated and applied to biomass samples with a mass of 2 kg by spraying the water evenly onto the material. The wetted material was

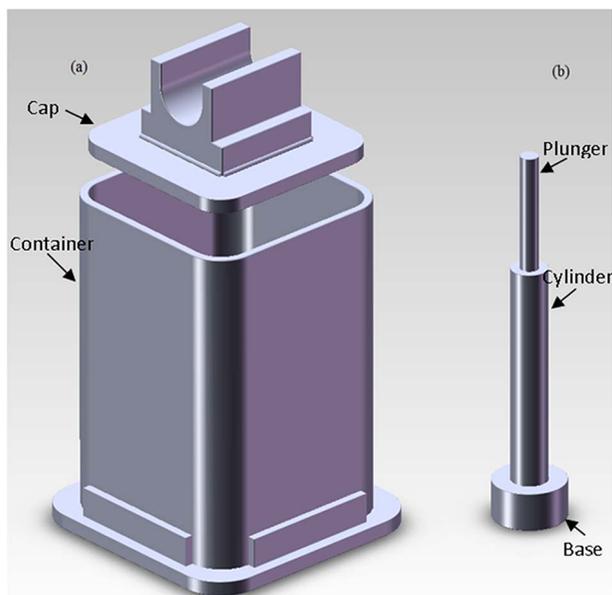


Figure 1. (a) Mini-bale compression arrangement with a dimension of 15.0 × 15.0 × 20.3 cm, constructed from steel tubing with a wall thickness of 6.35 mm. The 12.7 mm thick cap was fitted with a socket that matched the cross-tube mounting style of the hydraulic cylinder. (b) Plunger-in-cylinder pelletization arrangement, constructed in two versions, having 12.7 and 25.4 mm plunger diameters.

placed into a sealed plastic trash liner, which was placed in a covered garbage bin. This bin was stored at 22–25 °C for 72 h to achieve an equilibrium moisture content.²³ The moisture-conditioning error was controlled within ±3%.

To prepare the material for pelletization experiments, the moisture content of the biomass was adjusted to 15% using a mini temperature–humidity chamber (MR-148, TechTools, Inc., Brooklyn, NY) by following the isotherm curve procedure of the ASAE D245.6 (Oct 2007) standard. The chamber temperature was set to 13.0 °C, and the relative humidity was controlled to 89.0 ± 2% with a saturated NaCl solution.³¹ The samples were placed in the chamber for more than 3 weeks. Every day, the samples were weighed with an accuracy of ±0.1 mg. An equilibrium state was assumed when three consecutive weight measurements showed a difference of less than 1 mg.

2.2.3. Feedstock Preheating. The pelletization experiments were conducted at three temperature levels, being room temperature (22 °C), 75 and 125 °C. To control the preheating temperatures, a dual element heating tape with an embedded thermocouple was wrapped tightly around the plunger and connected to a temperature controller (Digi-Sense Benchtop RTD-Thermocouple-Thermistor, Cole-Parmer Instrument, Inc., Vernon Hills, IL). For pelletization experiments, the material was removed from the storage container and the cylinder was filled with either 1.5 g (12.7 mm plunger) or 5.0 g (25.4 mm plunger) of material. A mercury-in-glass thermometer was placed inside the cylinder to monitor the feedstock temperature. As soon as the material reached the desired temperature, the material was immediately compressed to a hydraulic pressure of 5.5 MPa, which translated into a material pressure of 189.5 MPa for the 12.7 mm plunger and 47.4 MPa for the 25.4 mm plunger.

2.2.4. Composition of Binding Agents. Thin stillage and light steep water were obtained from a corn ethanol plant (Aventine Renewable Energy, Inc., Pekin, IL) and used as binding agents for pelletization experiments. Table 1 shows their composition. The binding agents were mixed with biomass at a rate of 20 mL per 100 g of biomass. The 20 mL liquid agents approximately contained 4.04 and 2.22 g of solids, such as ash, fat, and filtered and unfiltered solids for thin stillage and light steep water (Table 1). After fully mixing and blending, the samples were oven-dried at a temperature of 49 °C for 72 h to reduce the sample moisture content to less than 10% for pelletization.

Table 1. Chemical Composition of Binding Additive Agents

binding agents	solids (g/L)			
	unfiltered (total) solids	filtered (soluble) solids	ash (g/L)	fat (g/L)
steep water	93.04	93.08	15.80	0.02
thin stillage	52.45	53.30	5.33	0.0136

Otherwise, the moisture content of biomass samples was too high to be pelletized.

2.3. Instrumentation. A hydraulic compressor was built to measure the energy consumption of biomass densification and pelletization (Figure 2). The hydraulic cylinder with a bore and

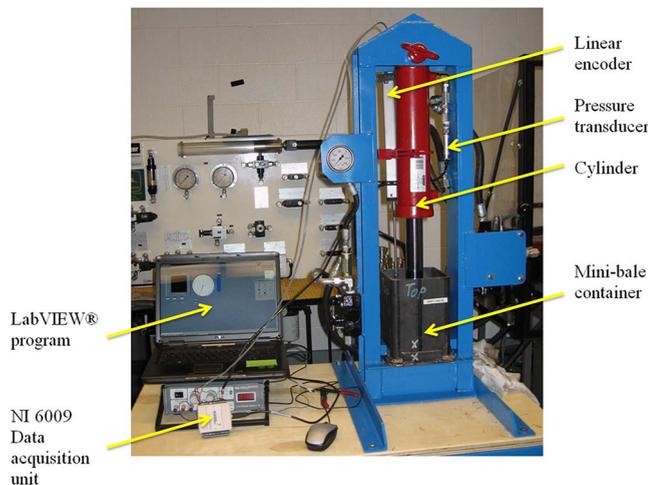


Figure 2. Compression apparatus consisting of a hydraulic cylinder and (in this photo) a mini-bale compression chamber. The apparatus was instrumented to read the hydraulic cylinder pressure and displacement using a NI 6009 data acquisition unit. LabVIEW, as shown here, was used for testing, whereas the experiments were conducted with a MatLab program as the data acquisition and analysis software.

stroke of 76.2 and 254 mm, respectively, was driven by a pump unit with a maximum flow rate of 11.25 L/min and a regulated maximum hydraulic fluid pressure of 5.5 MPa. During experiments, the pressure at the cap end of the hydraulic cylinder was measured using a transducer (PX603-5KG5 V, Omega Engineering, Inc., Stamford, CT), and the displacement of the piston was measured using a linear potentiometer (LP801-300, Omega Engineering, Inc., Stamford, CT). The fluid flow rate into the hydraulic cylinder was adjusted manually using a pressure-compensated flow control valve, such that extension time of the cylinder was between 20 and 30 s, implying a piston speed ranging from 8.5 to 12.7 mm/s. This fell within the range of industrial compression speeds, because the compression speed affects the energy efficiency of biomass densification.³² The pressure applied to the biomass was calculated as the measured cap end force divided by the cap end area of the hydraulic cylinder. The pressure on the rod end side of the cylinder during extension was assumed negligible, because it was directly connected to the reservoir and the cylinder extension speed was low. To check proper system functionality, a LabVIEW program was developed, as shown in Figure 2, but to combine data acquisition and analysis, it was replaced by a MatLab program. This program measured the displacement of the piston and the hydraulic cylinder pressure at a rate of 100 samples per second through a data acquisition module (NI 6009, National Instruments).

2.4. Data Analysis. The objective of the data analysis was to determine the energy required for compression of biomass in both the mini-bale and pelletizing arrangement and to reveal the underlying mechanism using empirical testing and regression analysis. By definition, the force (F) in N applied to the material is equal to the

measured pressure (p) at the cap end of the cylinder in Pa multiplied by the cap end area (A_{cap}) in m^2 .

$$F = pA_{\text{cap}} \quad (2)$$

The work performed during compression was calculated by integrating the force in N through the compression distance in m assuming an exponential model as follows:

$$W = \int_{x_1}^{x_2} F(x)dx = \int_{x_1}^{x_2} ae^{bx}dx = \frac{a}{b}e^{bx} \Big|_{x_1}^{x_2} = \frac{a}{b}(e^{bx_2} - e^{bx_1}) \quad (3)$$

where W in J is the work performed on the biomass during compression and $F(x)$ is the measured force as a function of the displacement x . The variables x_1 and x_2 are the initial and final piston positions, respectively, and a and b are parameters determined through regression analysis. A MatLab program was developed to perform regression analysis, calculate the energy requirement, and determine the bulk (or pellet) densities of the biomass.

Analysis of correlation, Student's t test, linear, and principal component regression were carried out with the PROC CORR, PROC TTest, PROC GLM, and PROC PRINCOMP modules of SAS 9.3 (SAS Institute, Inc., Cary, NC), respectively.

3. RESULTS AND DISCUSSION

3.1. Mini-bale Compression Experiments. Panels a and b of Figure 3 show the ultimate bulk density and energy consumption of mini-bale compression experiments to a material pressure of 1.2 MPa for *Miscanthus* (MI), switchgrass (SW), and willow (WI).

Figure 3a shows that the ultimate bulk density reached over 550 kg of DM m^{-3} for *Miscanthus* and willow and 480 kg of

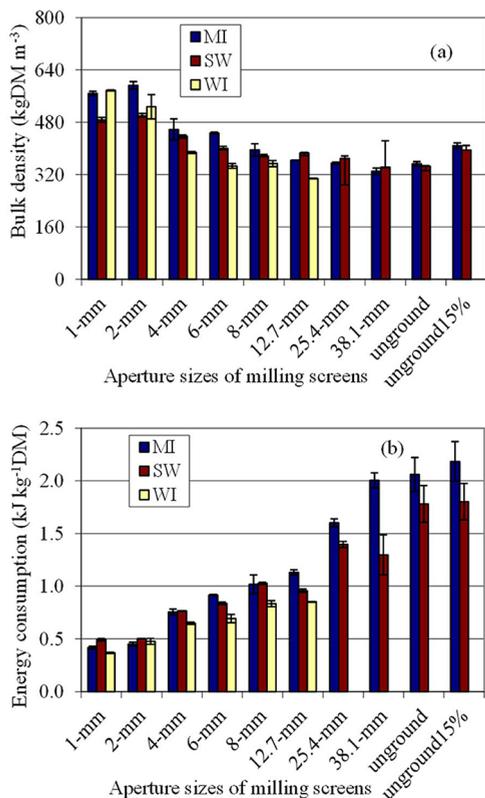


Figure 3. (a) Ultimate bulk density (kg of DM m^{-3}) and (b) energy consumption in kJ kg^{-1} of DM across aperture sizes of Retsch SM2000 knife mill screens for mini-bale densification at a maximum pressure of 1.3 MPa. MI, *Miscanthus*; SW, switchgrass; and WI, willow.

DM m^{-3} for switchgrass. The ultimate bulk densities of compressed *Miscanthus*, switchgrass, and willow were inversely proportional to the sizes of particles ground through screens with apertures ranging from 1 to 38.1 mm. Given the maximum pressure of 1.2 MPa, the regressions between the ultimate bulk densities (kg of DM m^{-3}) and aperture sizes (mm) of the Retsch SM2000 knife mill screens were

$$y = -5.8450x + 509.98 \quad (R^2 = 0.61, p < 0.0225) \quad \text{for } \textit{Miscanthus} \quad (4)$$

$$y = -3.4219x + 454.09 \quad (R^2 = 0.62, p < 0.0206) \quad \text{for switchgrass} \quad (5)$$

$$y = -28.7379x + 565.54 \quad (R^2 = 0.84, p < 0.0099) \quad \text{for willow} \quad (6)$$

For unground feedstock, the ultimate bulk density of *Miscanthus* and switchgrass biomass reached 352.8 and 345.9 kg of DM m^{-3} , respectively. These values were lower than the compressed bulk density of *Miscanthus* and switchgrass particles ground through a 12.7 mm milling screen of 362.7 and 386.3 kg of DM m^{-3} , respectively (Figure 3a).

A proportional relationship was found between the moisture content of unground biomass and the ultimate bale bulk densities at the given maximum material pressure of 1.2 MPa. The resulting densities at a moisture content of 15% were 408.4 and 395.3 kg of DM m^{-3} for *Miscanthus* and switchgrass, respectively. These values were significantly higher than those of air-dried *Miscanthus* and switchgrass with 7–10% of moisture content, which were 352.8 and 345.9 kg of DM m^{-3} , respectively. This effect may be attributed to the positive contribution of the biomass moisture content to the softening of biomass particles.

Figure 3b shows the energy consumption during mini-bale compression experiments for various materials. The energy consumption to compress biomass to an ultimate pressure of 1.2 MPa was proportional to the particle size. The relationships between specific energy consumption (kJ kg^{-1} of DM) and aperture size (mm) of the Retsch knife mill screens were

$$y = 0.041x + 0.54 \quad (R^2 = 0.95, p < 0.0001) \quad \text{for } \textit{Miscanthus} \quad (7)$$

$$y = 0.022x + 0.64 \quad (R^2 = 0.76, p < 0.0048) \quad \text{for switchgrass} \quad (8)$$

$$y = 0.054x + 0.37 \quad (R^2 = 0.94, p < 0.0015) \quad \text{for willow} \quad (9)$$

Figure 4 indicates that the energy consumption–bulk density relationships can be expressed parsimoniously in exponential curves for all biomass types and forms (note that the reciprocal value of bulk density is the specific volume in $\text{m}^3 \text{kg}^{-1}$ of DM as shown on the x axis). The particle size significantly influenced the energy consumption–bulk density curves. For instance, to achieve a bulk density of 310 kg of DM m^{-3} , the energy requirement to compress 8 mm *Miscanthus* was approximately 3 times higher than for 4 mm particles. Similarly, for unground *Miscanthus* (152–203 mm), the energy requirement was approximately 3 times higher than for 8 mm particles. These

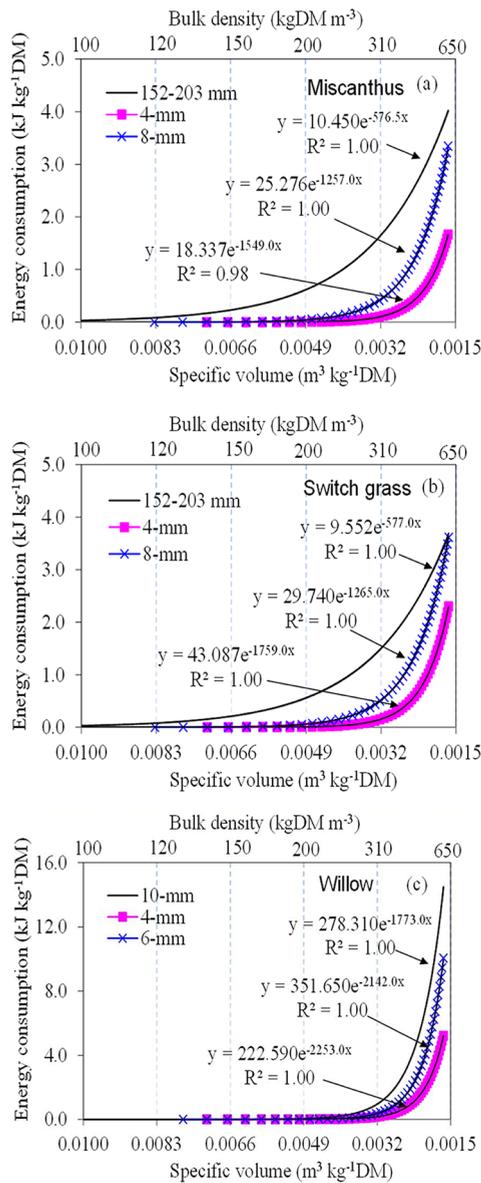


Figure 4. Particle size impact on specific energy consumption (kJ kg^{-1} of DM) of mini-bale densification for (a) *Miscanthus* (MI), (b) switchgrass, and (c) willow. For the regressions, y = specific energy consumption (kJ kg^{-1} of DM) and x = specific volume ($\text{m}^3 \text{kg}^{-1}$ of DM).

results imply that, by combining coarse size reduction and densification, both the energy efficiency of compression and ultimate bale bulk density would be significantly increased. For example, the energy and pressure of a Case New Holland baling machine with a chamber pressure of 0.5–1 MPa is enough to compress the 5–8 cm long *Miscanthus* to more than 300 kg DM m^{-3} . The bulk density of 300 kg DM m^{-3} was approximately equal to twice the average bale bulk density (i.e., 160 kg DM m^{-3}) and $1/3$ higher than that of a so-called densified bale (230 kg DM m^{-3}), which was baled with 15 cm *Miscanthus* chips by a Case New Holland baling machine.²¹

The results also imply that biomass baling is not constrained by energy consumption but rather by allowable stresses in machine components and costs. To increase the bale bulk density and energy efficiency of compression while reducing the compression machine scale, a single pass harvest–chopping–

baling–handling (HCBH) combine would be advantageous. This machine could be equipped with a traditional cutter head for coarse size reduction, chopping (or shredding) knife, baling components, and a bale loading lifter. The major advantages of the HCBH machine include high energy efficiency of compression, high compressed bulk density, and a combination of mechanical preprocessing before transportation and storage. This would improve the efficiency and also simplify the logistics of grass feedstock supply. For example, after in-field cutting and collecting biomass, the biomass is directly chopped into 6–12 in. long chips without in-field windrowing. Subsequently, the chips are baled and wrapped with biomass-based netting (e.g., hemp netting), because strings used in a traditional bale machine may not work well for the chopped biomass. With reduced biomass loss, the single-pass HCBH machine features simple logistics of collection and mechanical preprocessing in comparison to conventional two-pass harvest methods. Because the biomass is already coarsely chopped into 6–12 in. chips during harvesting, the feedstock can be directly fed into a hammer mill for finer size reduction. The HCBH combine is in agreement with the “uniform” or “advanced uniform” supply logistics concept.^{5,6} Prototype design and in-field evaluation of a HCBH combine needs to be conducted in the future.

3.2. Pelletization Experiments. **3.2.1. Effect of the Particle Size on Pellet Density and Energy Consumption.** Figure 5a shows a weak inverse proportionality between the particle size and pellet density. Under a maximum material pressure of 47.4 MPa, the pellet density of corn stover was significantly higher than that of *Miscanthus*, switchgrass, and willow.

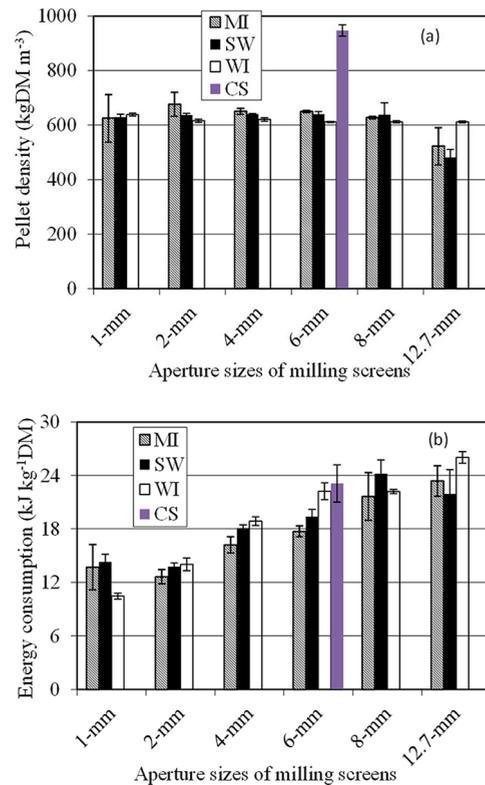


Figure 5. (a) Particle size impact on pellet density (kg DM m^{-3}) and (b) specific energy consumption (kJ kg^{-1} of DM) of feedstock pelletization at a maximum pressure of 47.4 MPa. MI, *Miscanthus*; SW, switchgrass; WI, willow; and CS, corn stover.

Figure 5b shows that the compression energy consumption and particle size exhibit a proportional relationship. The regressions between energy consumption and aperture size of the knife mill screens were

$$y = 0.955x + 12.183 \quad (R^2 = 0.93, p < 0.0021)$$

for *Miscanthus* (10)

$$y = 0.810x + 14.055 \quad (R^2 = 0.72, p < 0.0331)$$

for switchgrass (11)

$$y = 1.597x + 10.713 \quad (R^2 = 0.93, p < 0.0021)$$

for willow (12)

where y is the specific energy consumption of pelletization (kJ kg^{-1} of DM) and x is the aperture size (mm) of the Retsch knife mill screens. Similar to the mini-bale compression, the correlations between pelletization energy consumption and particle sizes of *Miscanthus* and willow were more significant than those of switchgrass.

3.2.2. Effect of Feedstock Preheating on Pellet Density. Figure 6a shows the effects of preheating on the relationship between the pellet density and particle size after compression to an ultimate pressure of 47.4 MPa. In general, preheating led to higher pellet densities. The effect of the preheating temperature was more pronounced for larger diameter particles for *Miscanthus* and switchgrass. For example, at 22 °C, the pellet density was inversely proportional to the biomass particle size for *Miscanthus* and switchgrass. At 75 and 125 °C, however, there were no significant relationships between the pellet density and particle sizes for *Miscanthus* and switchgrass (panels a and b of Figure 6).

Figure 6c shows the same relationship between the pellet density and particle size for increased temperatures for willow particles. Here, the overall effect of increased bulk density for increased temperatures holds true, but the effect was no longer more pronounced for larger particle sizes.

Figure 6 also demonstrates that the effects of the preheating temperature were minimized for higher temperatures for *Miscanthus* and switchgrass. With the exception of two data points, a temperature of 75 °C resulted in higher densities than a temperature of 125 °C. This effect was not a function of the material, which indicates the potential existence of an optimal temperature to attain an increased pellet density compared to what is attainable at room temperature. The reason why the 75 °C experiments resulted in a higher density than the 125 °C experiments could be attributed to evaporation of moisture at 125 °C, but this hypothesis was not tested. The effect is however in agreement with the conclusion that the resulting densities at a moisture content of 15% were higher than those at a moisture content of 10% for *Miscanthus* and switchgrass in mini-bale experiments.

3.2.3. Effect of Feedstock Preheating on Pelletization Energy Requirement. Figure 7 shows that preheating significantly decreased the energy requirement of pelletization for all materials under test. At the three preheating levels of 22, 75, and 125 °C, while applying an ultimate pressure of 47.4 MPa, the energy consumption of compression for *Miscanthus*, switchgrass, and willow were all proportional to the particle size. At room temperature (22 °C), the pelletization energy consumption as a function of the aperture size of the knife mill screens are as follows:

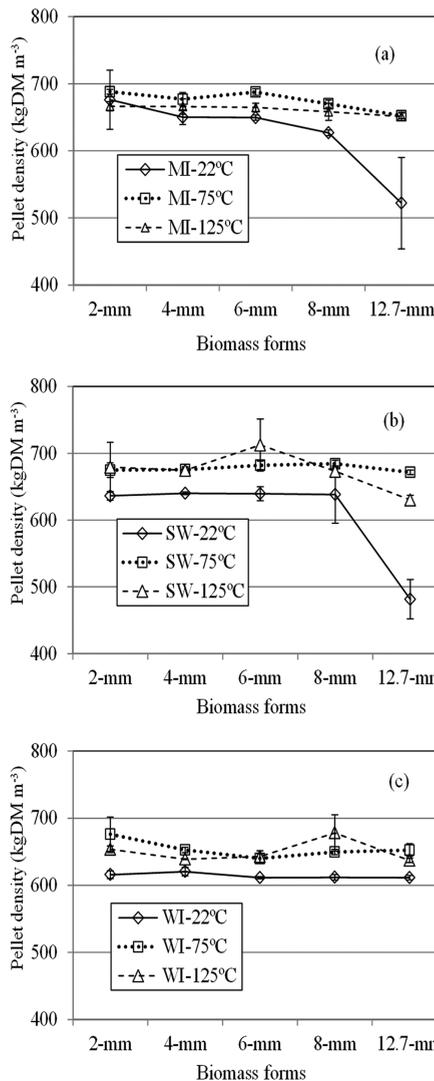


Figure 6. Preheating impact on pellet density (kg of DM m^{-3}) at a maximum pressure of 47.4 MPa for (a) *Miscanthus* (MI), (b) switchgrass (SW), and (c) willow (WI).

$$y = 1.073x + 8.20 \quad (r^2 = 0.99, p < 0.0006)$$

for *Miscanthus* (13)

$$y = 0.550x + 12.39 \quad (r^2 = 0.99, p < 0.0005)$$

for switchgrass (14)

$$y = 0.846x + 11.67 \quad (r^2 = 0.89, p < 0.0164)$$

for willow (15)

where y is the specific energy consumption (kJ kg^{-1} of DM) of feedstock pelletization at room temperature (22 °C) and x is the aperture size (mm) of Retsch SM2000 knife mill screens.

There was not a monotonically decreasing trend for energy consumptions among the three temperatures, but instead, the 75 °C experiments required slightly less energy than the 125 °C experiments across all particle sizes. A similar trend was found for switchgrass and willow (panels b and c of Figure 7). Again, the reason why the 75 °C experiments required less energy than the 125 °C experiments might be evaporation of moisture at 125 °C. Further studies are needed to test this hypothesis.

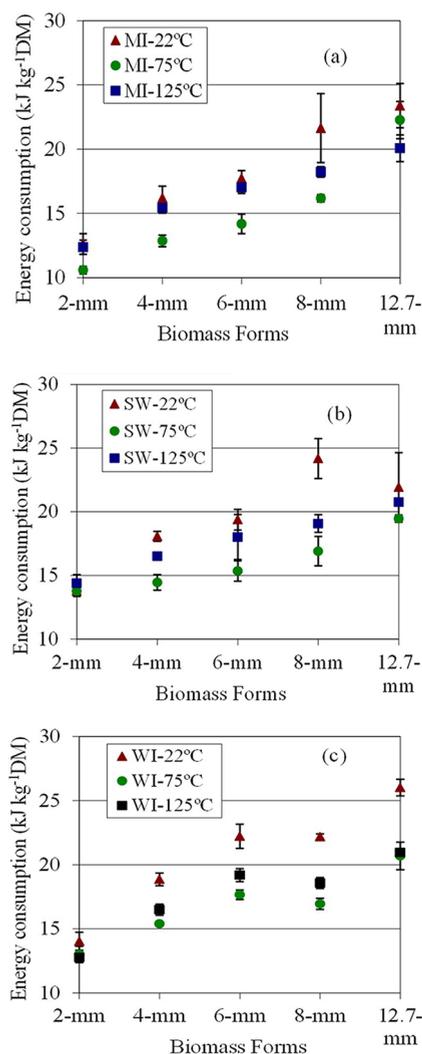


Figure 7. Preheating impact on specific energy consumption (kJ kg^{-1} of DM) of pelletization at a maximum pressure of 47.4 MPa for (a) *Miscanthus* (MI), (b) switchgrass (SW), and (c) willow (WI).

3.2.4. Effect of Binding Agents on Pelletization Energy Requirement. Under the maximum applied pressures of 47.4 and 189.5 MPa, binding agents slightly increased the energy consumption of pelletization at the rate of 20 g of binding agent per 100 g of biomass sample compared to that of non-agent compression, particularly for switchgrass (Figure 8). For instance, under a maximum pressure of 47.4 MPa, the energy consumption of compression was 15.3 kJ kg^{-1} of DM for 1 mm *Miscanthus* mixed with 20 g of steep water per 100 g of biomass. This was higher than that of 13.7 kJ kg^{-1} of DM for non-agent *Miscanthus*. The results imply that, with binding agents, the dry feedstock particles became harder and stiffer and required more energy to compress. However, the binding agents increased the hardness and durability of pellets. These results indicated that there is potential to apply binding agents from corn ethanol production to lignocellulosic feedstock production. Although other materials, including molasses and starch, could be used as binding agents, the wastes, such as stillage and steep water, from an industry are preferred to be used as binding agents for the sake of clean energy.

3.2.5. Contribution Sequences of Variables to Pelletization. On the basis of the principal component regression analysis, the contributions of the variables, including crop

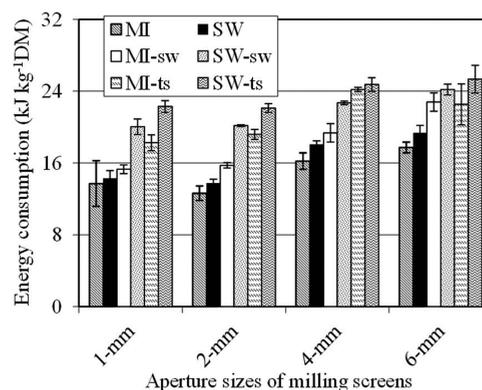


Figure 8. Binding agent effects on specific energy consumption (kJ kg^{-1} of DM) of *Miscanthus* (MI) and switchgrass (SW) pelletization at a maximum pressure of 47.4 MPa. MI-sw, SW-sw, MI-ts, and SW-ts symbolize *Miscanthus* and switchgrass mixed with 20 g of steep water and thin stillage per 100 g of biomass sample, respectively. MI and SW symbolize biomass samples without binding agents.

species, maximum applied pressure, particle size, preheating, moisture content, and binding agents, i.e., the absolute values of principal component regression coefficients, were ranked as crop species (2.07) > moisture content (-1.41) > particle size (1.26) > maximum pressure (0.14) > preheating (-0.11) > binding agents (0.05). In other words, under a given maximum pressure (i.e., with a specific pelletization machine), the moisture content, temperature, and particle size played the most important roles in reducing the pelletization energy for a specific biomass type. Therefore, the energy consumption of feedstock pelletization could be significantly reduced by optimizing the feedstock moisture content, preheating temperature, and particle size.

4. CONCLUSION

The energy consumption–bulk density relationships of *Miscanthus*, switchgrass, willow, and corn stover feedstock had an exponential form for both mini-bale compression and pelletization. For the mini-bale compression, the particle size and moisture content significantly influenced the energy consumption of compression.

For feedstock pelletization, under a given maximum pressure, the preheating temperature, particle size, and moisture content played significant roles in reducing the energy requirement and increasing the pellet density for a given crop species and a maximum applied pressure.

Binding agents increased the pelletization energy requirement of *Miscanthus* and switchgrass but resulted in increased pellet durability.

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Notes

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