Review

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A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application†

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Abstract: Developing uniformly formatted, densified feedstock from lignocellulosic biomass is of interest to achieve consistent physical properties such as size and shape, bulk and unit density, and durability, which significantly influence storage, transportation and handling characteristics, and, by extension, feedstock cost and quality. A variety of densification systems are considered for producing a uniform format feedstock commodity for bioenergy applications, including (i) pellet mill, (ii) cuber, (iii) screw extruder, (iv) briquette press, (v) roller press, (vi) tablet press, and (vii) agglomerator. Each of these systems has varying impacts on feedstock chemical and physical properties, and energy consumption. This review discusses the suitability of these densification systems for biomass feedstocks and the impact these systems have on specific energy consumption and end-product quality. For example, a briquette press is more flexible in terms of feedstock variables where higher moisture content and larger particles are acceptable for making good quality briquettes; or among different densification systems, a screw press consumes the most energy because it not only compresses but also shears and mixes the material. Pre-treatment options like pre-heating, grinding, steam explosion, torrefaction, and ammonia fiber explosion (AFEX) can also help to reduce specific energy consumption during densification and improve binding characteristics. Binding behavior can also be improved by adding natural binders, such as proteins, or commercial binders, such as lignosulfonates. The quality of the densified biomass for both domestic and international markets is evaluated using PFI (United States standard) or CEN (European standard). Published in 2011 by John Wiley & Sons, Ltd

Keywords: densification systems; biomass density; densification energy; biomass pre-treatment; biomass quality; solid fuel standards

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Introduction

Behind only coal and oil, biomass stands as the third-largest energy resource in the world.[1] One of the major limitations of using biomass as a feedstock for bioenergy products is its low bulk density (wet basis), which typically ranges from 80–100 kg/m^3 for agricultural straws and grasses and 150–200 kg/m^3 for woody resources like wood chips and sawdust.[2,3] The low densities of biomass often make the material difficult to store, transport, and interface with biorefinery infeed systems. For example, when low-density biomass is co-fired with coal, the difference in density causes difficulties in feeding the fuel into the boiler and reduces burning efficiencies.[4] One way to overcome this limitation is to increase biomass density, which has the added benefit of increasing the material's unit density as much as ten-fold.[5]

The densification process is critical for producing a feedstock material suitable as a commodity product. Densification enables several advantages, including (i) improved handling and conveyance efficiencies throughout the supply system and biorefinery infeed, (ii) controlled particle size distribution for improved feedstock uniformity and density, (iii) fractionated structural components for improved compositional quality, and (iv) conformance to pre-determined conversion technology and supply system specifications.

Common biomass densification systems have been adapted from other highly efficient processing industries like feed, food, and pharmacy, and include (i) pellet mill, (ii) cuber, (iii) briquette press, (iv) screw extruder, (v) tabletizer, and (vi) agglomerator. Among these, the pellet mill, briquette press, and screw extruder are the most common ones used for bioenergy production. The quality of densified biomass produced using these systems is evaluated with the existing international standards developed for pellet mill and briquette press systems; there are no system-specific standards developed for the others.

A number of studies have been performed on densification of herbaceous and woody biomass using pellet mills and screw/piston presses. Ndiema *et al.*[6] examined the influence of die pressure on relaxation characteristics of briquetted biomass. Adapa *et al.*[7,8] studied pelletization of fractionated agricultural straws. Li and Liu[9] investigated high-pressure densification of wood residues to form an upgraded fuel. Mani *et al.* [10] researched the compaction characteristics of lignocellulosic biomass using an Instron Universal Testing Machine.

Most existing literature on densification focuses largely on understanding densification mechanisms and quality attributes. This review provides context for these considerations in development of advanced biomass feedstock supply systems that meet biorefinery needs at a commodity scale. It identifies advantages and limitations of using different densification systems to create advanced feedstocks with defined size, shape, and bulk flowability properties for bioenergy applications.

A variety of approaches is discussed for understanding the role of densification in development of advanced uniform feedstocks for bioenergy applications, including (i) mechanisms of particle bonding during densification, (ii) different densification systems such as pellet mill, briquette press, cuber, tablet press, roller press, screw extruder and agglomerator, (iii) specific energy consumption of different densification systems, (iv) effects of densification process variables on quality of the densified products and (v) effects of pre-treatments, such as grinding, pre-heating, steam explosion, torrefaction, and ammonia fiber explosion (AFEX process) on densification process. Finally, advantages of particular systems are discussed in relationship to bioenergy applications and recommendations are made for future studies.

Mechanisms of bonding of particles during densification

The quality of densified biomass depends on strength and durability of the particle bonds, which are influenced by a number of process variables, like die diameter, die temperature, pressure, binders, and pre-heating of the biomass mix. Tabil[11] and Tabil and Sokhansanj[12,13] suggested that the compaction of biomass during pelletization can be attributed to elastic and plastic deformation of the particles at higher pressures. According to their studies, the two important aspects of pelletization are (i) the ability of the particles to form pellets with considerable mechanical strength, and (ii) the ability of the process to increase density.

The first is a fundamental behavior that details which type of bonding or interlocking mechanism results in better densified biomass. Rumpf[14] and Sastry and Fuerstenau[15]

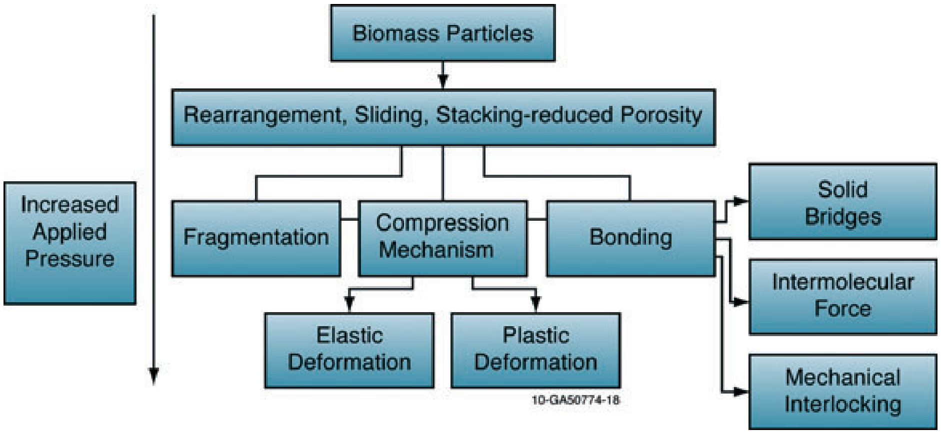

Figure 1. Deformation mechanisms of powder particles under compression.

suggested that the mechanism of binding during agglomeration can be from the formation of solid bridges. These solid bridges are developed by chemical reactions and sintering solidification, hardening of the binder, hardening of the melted substances, or crystallization of the dissolved materials. The pressure applied during densification reduces the melting point of the particles and causes them to move toward one another, thus increasing the contact area and changing the melting point to a new equilibrium level.[16,17] Presence of liquids, like water, during densification results in interfacial forces and capillary pressures that increase particle bonding. Schineberger[18] mentioned that the attraction between the particles is due to the van der Waals electrostatic or magnetic forces, and is inversely proportional to the distance between the particles, where larger distances have less attraction.

Mani *et al.*[19] postulated three stages during densification of biomass. First, particles are rearranged to form a closely packed mass where most of the particles retain their properties and the energy is dissipated due to inter-particle and particle-to-wall friction. Second, the particles are forced against each other and undergo plastic and elastic deformation, which significantly increases the inter-particle contact; particles become bonded through the van der Waals and electrostatic forces. Third, a significant reduction in volume results in the density of the material reaching the true density of the component ingredients. By the end of the third stage, the deformed and broken particles can no longer change their position due to a decreased number of cavities with a 70% inter-particle conformity. It is also important to understand that the yield point of the material governs the rate of approach to the true density of the product. Because the loading is hydrostatic in character, the application of pressure will fracture the brittle particles. These processes may also result in mechanical interlocking. Figure 1 shows the deformation mechanism of the powder particles under compression.[20,21]

Biological material behavior is more complex during loading and may have different deformation characteristics compared to powders compaction. Research on understanding the compaction behavior of biomass using the rheological models that take into account the viscoelastic nature of the material is still in initial stages.[22]

The chemical composition of biomass, which includes cellulose, hemicelluloses, protein, starch, lignin, crude fiber, fat, and ash, also affects the densification process. During compression at high temperatures, the protein and starch plasticizes and acts as a binder, which assists in increasing the strength of the pellet.[23–26] Lignin in the biomass at temperatures above about 140°C softens and improves the binding of the particles.[7,12,13,27] Scanning electron microscopes (SEMs) have been used to understand the solid-type bridges formed during briquetting and pelleting of corn stover and switchgrass.[28] More studies at a micro level using techniques like SEM and transmission electron microscope (TEM) will be useful in understanding intra-particle cavities, material properties, and process variable interactions on the quality attributes of densified biomass.

Densification systems

Pellet mill

Pelletization is a popular processing technique in feed and fuel manufacturing. In simple terms, pelleting converts finely ground ingredients into dense, free-flowing, durable pellets.[29,30] A pellet has uniform product characteristics in terms of size (length and diameter: 13–19 mm and 6.3–6.4 mm), shape (cylindrical), and unit densities (1125–1190 kg/m^3).[5]

A pelletizer consists of a perforated hard steel die with one or two rollers (Fig. 2).[29] By rotating the die and rollers, the feedstock is forced through the perforations to form densified pellets.[31]

Pellet presses consist of two types: ring die and flat die. In both machines, the die remains stationary and the rollers rotate. Some rotating die pellet mills are available in which the rollers remain stationary during the production process.[32]

The pellet mill operation starts with incoming biomass flowing into the conditioner for the controlled addition of steam. The steam softens the feed and partially gelatinizes the starch to create more durable pellets. Most mills have one or more conditioning units mounted above the main unit. From the conditioner, the feed is discharged over a permanent magnet and into a feed spout leading to the pelleting die. Inter-elevator flights in the die cover feed the mash evenly to each of the two rolls. The feed distributor flights spread the material across the face of the die. Then friction-driven rolls force the feed through holes in the die as the die revolves. Cut-off knives mounted on the swing cover cut the pellets as they are extruded from the die, and finally the pellets fall through the discharge opening in the swing door.[31]

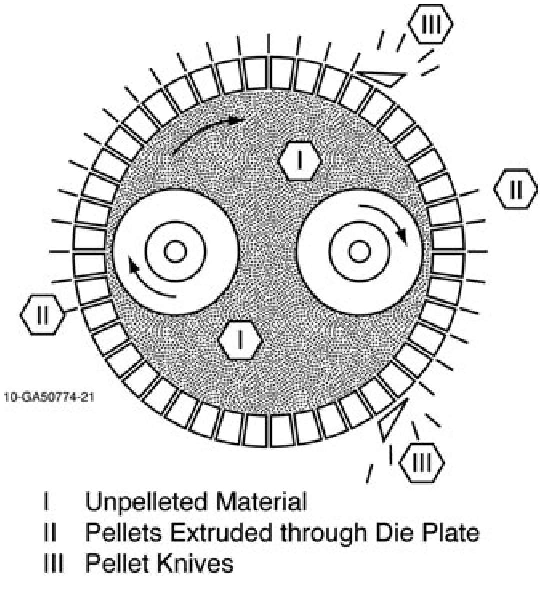

Figure 2. Working process of a pellet mill die.

Typical commercial units have two rollers to meet the high production rates in the range of 2.5–5 t/hr.[29] Power consumption of the pellet mills falls within the range of 15–40 kWh/ton.[33]

Briquette press

Briquetting is usually performed using hydraulic, mechanical, or roller presses. Unlike pellet mills, briquetting machines can handle larger-sized particles and wider moisture contents without the addition of binders. Grover and Mishra[33] found that agricultural material briquettes can be formed at 22% moisture content using briquette machines. They also suggest that briquettes offer advantages, such as (i) better feed handling characteristics, (ii) higher calorific value, (iii) improved combustion characteristics, (iv) reduced particulate emissions, and (v) more uniform size and shape. In addition, briquettes can be used in furnaces where other solid fuels like wood pellets are used.[33] A typical schematic of a mechanical or hydraulic press is shown in Fig. 3.[34]

During briquetting, the moisture in the material forms steam under high pressure, hydrolyzing the hemicellulose and lignin into lower molecular carbohydrates, lignin products, sugar polymers, and other derivatives.[33] These products, when subjected to heat and pressure in the die, act as adhesives and bind the particles together.[33] Further addition of heat helps in relaxing the biomass fibers and softens the structure.[33] Briquettes produced using a hydraulic press have uniform shape and size, typically 40 × 40-mm cylinders, and unit densities in the range of 800–1000 kg/m^3.[35]

Hydraulic piston press

Hydraulic piston presses are commonly used as briquetting machines. The output is lower compared to mechanical presses because the movement of the cylinder is slower. The required pressure in the hydraulic press is produced by a specially designed hydraulic cylinder that releases the compressed briquette once the required pressure is reached. The pressure is adjusted using a

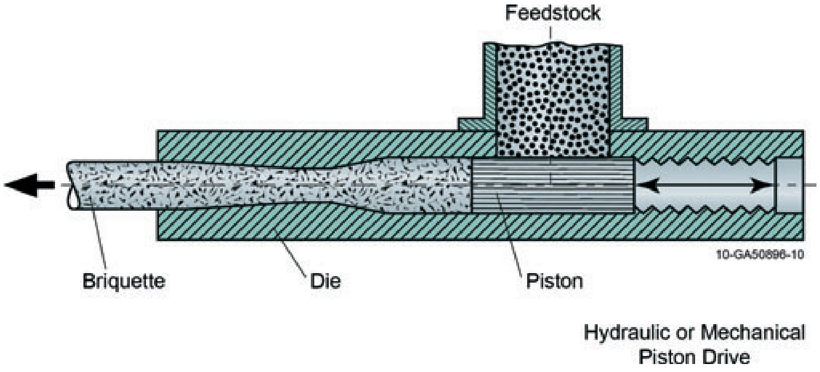

Figure 3. Mechanical or hydraulic piston press.

regulator to maintain consistency. Briquettes have a unit density lower than 1000 kg/m³ because of limited pressure. The typical production capacities of these machines are in the range of 50–400 kg/hr. However, these machines can tolerate higher moisture contents than the usually accepted 15% for mechanical piston presses.[36]

Mechanical piston press

The mechanical briquetting press develops a compression force of approximately 2000 kg/cm^2 to obtain high quality briquettes with high unit densities (>1000 kg/m^3) and without the addition of binders. Mechanical piston presses are typically used for large-scale production, ranging from 200–2500 kg/hr. Energy loss in the machine is limited, and the output in relation to power consumption is optimal. The operating life of a mechanical press is considerably longer than hydraulic presses. Generally, a mechanical press gives a better return on investment than a hydraulic press.[36]

Tabletizer

A tabletizer tightly presses biomass with a hydraulic motor and ram in a 4 to 6-in. diameter cylindrical mold, reducing the material from about 10 to 2-in. (smaller than most biomass briquettes) (Fig. 4).[37] The application of about 20 000 psi in the mold is sufficient to force the material to adhere together without adding binders. Long, coarse-cut feedstocks are favorable in the process, as they stick together more easily. Tablet densities average 55 lb/ft^3 compared to bale at 10 lb/ft^3 and pellets at 45 lb/ft^3. However, the tableting process uses more energy than pelletization. The tablets have not been tested extensively for various biomass resources and for energy density. Suitability of the tableting process has not been evaluated for power plant or gasification process feedstocks. Research is ongoing to determine the energy requirements for making tablets and the scale-up process to

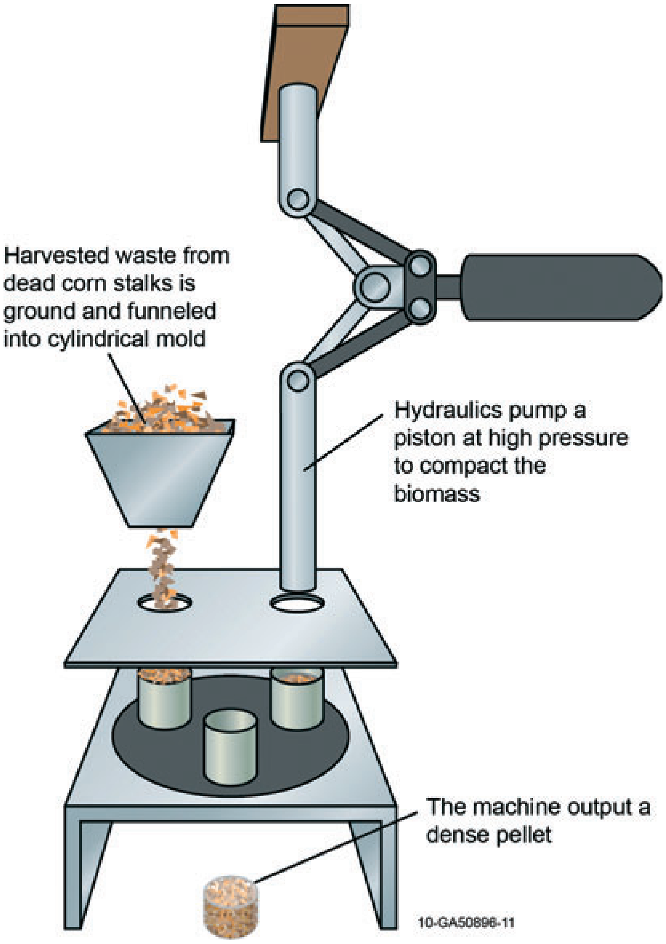

Figure 4. Energy tablet-making machine for biomass.

be followed in the case of large-scale production and product application in the areas of co-firing and gasification.[38]

Cuber

The cuber die ring and press roller (wheel) are similar to the die ring of a pelleter (Fig. 5).[39] An auger moves the chopped biomass uniformly toward the openings in the die ring. As the material leaves the auger flight, the heavy press wheel forces the feed through the die openings in the ring. The pressures in a cuber range from 24 to 34 MPa. The natural binders in chopped biomass, the high pressure of the press wheel, and heat generated by forcing biomass through dies help bond the cubes. An adjustable deflector around the outside of the die ring breaks the cubes in lengths of 50 to 75 mm.[39,40] Cubing operators often find it necessary to add a binder to increase cube durability. Typical binders used are bentonite, hydrated lime, starch, lingo-sulfonates (by-product from pulp and paper operation), agro colloids, and other commercial binders.[39,40]

Roller press

Roller presses consist of two rollers of the same diameter, rotating horizontally in opposite directions on parallel axes (Fig. 6).[41] Ground biomass, when forced through the gap between the two rollers, is pressed into small pockets, forming the densified product. Because the rotation of the rollers is in opposite directions, the biomass is drawn in one side and the densified product is discharged out the opposite side. The distance between the two rollers, referred to as the gap, depends on many factors such as the type of biomass, the particle size, the moisture content, and the addition of binders.[41] Design parameters that play a major role on the quality of the densified product are diameter of the rollers, gap width, roller force, and shape of the die. Typical bulk densities range from 450 to 550kg/m^3.[42]

Screw extruder

Extrusion brings small particles <4 mm close together so that the forces acting between them become stronger, providing more strength to the densified bulk material. During extrusion, biomass moves from the feed port, with a rotating screw, through the barrel and against a die, resulting in a significant pressure gradient and friction due to shearing of the biomass.[33] The combined effects of wall friction at the barrel, internal friction in the material, and high rotational speed (~600 rpm) of the screw, increase the temperature of the biomass. The heated biomass is further forced through the extrusion die to form briquettes or pellets. External heat using band or tape heaters is provided if the heat generated within the system is not sufficient to reach a pseudoplastic state for smooth extrusion.[33] Figure 7 shows the typical extruder, with different zones for processing of biomass.[43]

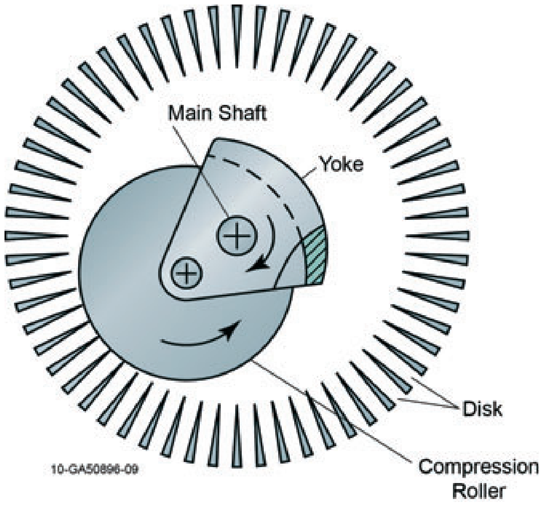

Figure 5. Press wheel and die arrangement in a cuber mill.

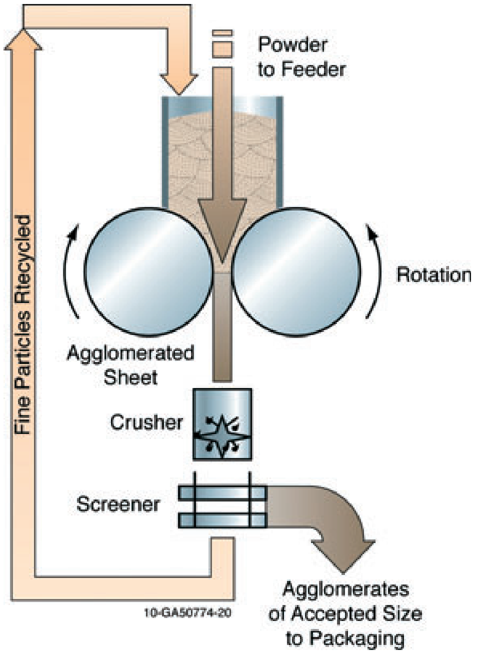

Figure 6. Roller press mill.

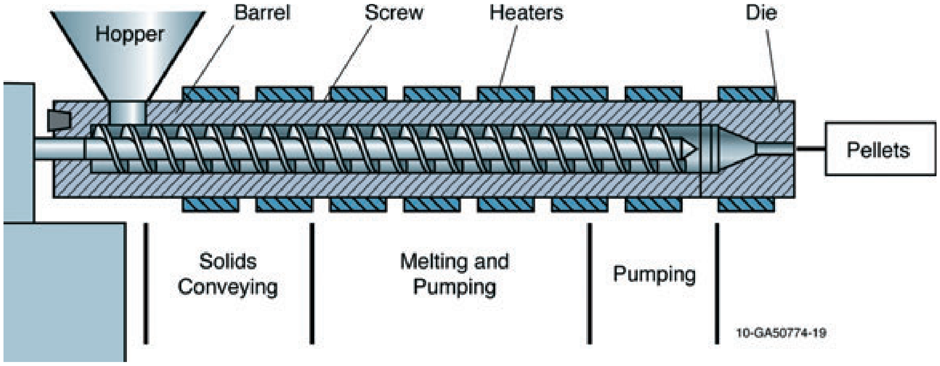

Figure 7. Extruder for biomass or polymer processing.

Processing of biomass using screw extruder occurs in four stages: (i) solids conveyance; (ii) initial compression; (iii) final compression; and (iv) discharge.[33] During solids conveyance, ground biomass is partially compressed and packed, and maximum energy is required to overcome particle friction. During initial compression, biomass particles become relatively soft and lose their elastic nature due to high temperature (200–250°C), resulting in the formation of local bridges and interlocking particles. The biomass also absorbs energy from friction so that it may be heated and mixed uniformly through its mass. Smaller particle sizes (2–4 mm depending on die diameter) are normally preferred during extrusion as they lead to better binding of the materials.[33,44] During final compression, biomass enters the tapered die, where moisture is further evaporated due to temperatures on the order of 280°C, helping to increase the compression of the material. Finally, during discharge, the pressure throughout the material normalizes, resulting in a uniform extruded log. The high temperatures used during extrusion result in charring of the material and make it more suitable for burning or co-firing applications. The physical properties of the cylinder-shaped extruded product are given in Table 1.

Table 1. General specification of extrudate produced by the Shimada SPMM 850 extrusion press.[145]

Raw material prior to extrusion (hard or soft wood)	
Moisture content (%)	8
Average particle size (mm)	2–6
Unit density (kg/m^3)	200
Extruded logs	
Moisture content (%)	4
Unit density (kg/m^3)	1400
Calorific value (kcal)	4870
Ash content (%)	0.35–0.5

Agglomerator

Agglomeration is a method of increasing particle size by gluing powder particles together. This system is used with a variety of powders such as hydrated lime, pulverized coal, iron ores, fly ash, cement, and others. The application of agglomeration for biomass is limited.[45,46] The most commonly used method is tumbling agglomeration, which consists of a rotating chamber filled with balls of varying sizes and fed with powder and often a binder. The rotation of the agglomerator results in centrifugal, gravitational, inertial, and frictional forces. These forces press the smooth rolling balls against the powder, helping them to stick together and the particle sizes to grow.[47] Different types of agglomerators are drum, pan, conical, and plate shaped.

A granulation agglomerator involves the following steps: (i) fine raw material is continually added to the pan and wetted by a liquid binder; (ii) the disc rotates causing the wetted fines to form small, seed-type particles (nucleation); and (iii) the seed particles 'snowball' by coalescence into larger particles until they discharge from the pan.[48]

For any particular agglomerator, the main process parameters are the ball residence time (depending on powder feed rate, acting volume, and pan-tilt angle) and proper rolling action (depending on scraper position, binder premixing, and pan-tilt angle). Mort[49] suggested that agglomeration is also a function of feedstock variables, such as particle size, distribution and shape, porosity, and surface chemistry, as well as process variables such as fluidization, residence time, temperature, and application energy (Fig. 8).[49] He also concluded that the addition of binders plays a significant role in the quality of the agglomerated powders. Typically, agglomerated materials are spherical with diameters ranging from 4–6 mm, depending on the residence time of the material in the agglomerator.

Specific energy requirements for densification

The specific energy requirements for biomass densification depend on the system used, process variables like temperature and pressure, feedstock variables like moisture content, particle size and distribution, and biochemical composition like starch, protein, fat and other lignocellulosic components.[50] Most densification processes involve both compression and extrusion work. Extrusion requires more energy than compression because the material has to overcome the friction during compression and pushing. The work performed during densification can be shown for both processes using Eqn (1):[50]

$$\mathrm{w} = A \int_0^x P \, dx \qquad (1)$$

where P is the applied pressure, x is the sample thickness, and A is the cross-sectional area of the die. In the compression apparatus, the density (D) at each point is calculated from as follows:[50]

$$D = m/xA \qquad (2)$$

where m is the sample mass.

Winter[51] postulates a power law or exponential relation to describe the specific energy (E_n) with respect to throughput:

$$E_n = aM_0^b \qquad (3)$$

where M_0 is the mass flow rate, and a and b are constants that vary with density and depend on die and feed characteristics. It was observed that the specific energy requirements decreased from 180–8 kWh/metric ton over a throughput range of 0.05–1.3 metric tons per hour (MTPH).

Winter[51] also calculated the specific energy required for pelletization. The material that passes through the

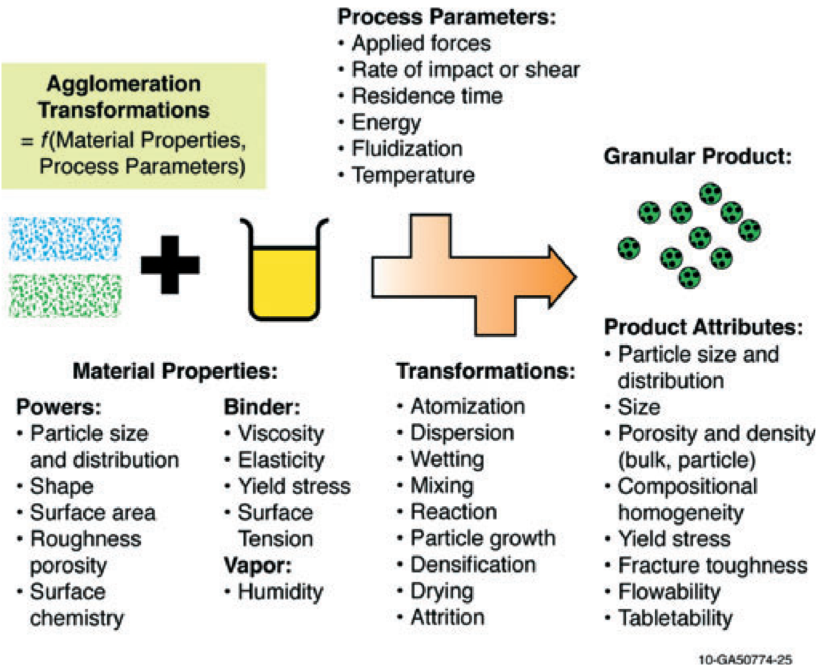

Figure 8. Agglomeration as a function of material properties and process parameters.

pellet die has to accomplish the following processes: precompress the loose feed, deform the feed as it enters the die, and balance the die frictional force as the pellet passes the die. The frictional force (F) is related to die length and diameter by:

$$F = F_0 \, exp \, \frac{4\mu L}{D} \qquad (4)$$

where F_0 is the initial frictional force, L is the die length; D is the die diameter, and μ is a constant.

The initial static friction that the pellet must overcome is greater than that which must be overcome when the pellet begins to flow. Stopping and starting the flows significantly increases the specific energy requirements. According to Reed *et al.*,[50] there are three types of pressure applications in commercial densification processes: (i) compression in a die; (ii) extrusion through a constriction; and (iii) shear of precompacted material to produce heat and flow under pressure. Table 2 shows the comparison of energy requirements for commercial densification systems.[50]

The required compression-specific energy is lower by a factor of 2 to 10 compared to commercial compression machines because the measurement does not include motor and bearing losses associated with commercial equipment (Table 3). Given this fact, laboratory results likely represent lower specific-energy requirements for densification. The specific-energy consumption for both compression and extrusion can be reduced by a factor of about two by preheating the biomass to 200–225°C before densification.[50] This extra heating prior to densification may require about 1.8 J/g-C. However, electrical power and equipment costs may be reduced due to lower pressure requirements and reduced die wear from improved lubricity. Furthermore, the fuel value or energy content may increase due to complete water removal and pre-pyrolysis, such that pellets made at 225°C have an energy content of 20.2 J.[50] Table 3 shows the effect of temperature and extrusion rate on refuse-derived fuel (RDF).

Mewes[52] concluded that only 37–40% of the input energy is required to compress the material; the remaining energy is required to overcome friction during compression. Mohsenin and Zaske[53] observed that increasing moisture content reduced the energy required to reach a specific density. O'Dogherty and Wheeler,[54] with barley straw in a circular die, noted an energy requirement of 5–25 MJ/t, depending on wafer density. Aqa and Bhattacharya[55] observed that when densifying preheated (115°C) sawdust, energy inputs to a briquetting machine motor, die heaters, and overall system were reduced by 54, 30.6, and 40.2%, respectively. The specific energy consumption for different

Table 2. Comparison of reported energy requirements for commercial densification apparatus with laboratory results.[50]

	Material	Unit Density (g/cc)	kWh/ tonne	kWh/ ton
Compression				
In laboratory[a]	Sawdust	1.0	4.0	3.6
	Sawdust	1.2	6.6	6.0
Commercial[b]	Sawdust	~1.2	37.4	34.0
Extrusion				
In laboratory[c]	Municipal Solid Waste	1.0	7.76	7.06
Commercial[d]	Municipal Solid Waste	1.0	16.4	14.9
	Sawdust	1.0	36.8	33.5

Note:
[a] 2.5-cm pellet
[b] From specifications of 150-hp Hausmann briquettor no. FH 2/90/200 for 8-cm diameter log.
[c] 1.2-cm pellet made at 25°C.
[d] Data supplied by California Pellet Mill Corp.

Table 3. Specific energy consumption during extrusion of RDF.[50]

	Energy	
	kWh/tonne	kWh/ton
Temperature[a] (°C)		
25	7.76	7.06
93	6.09	5.54
149	6.23	5.67
204	4.45	4.05
Extrusion rate[b] (cm/min)		
5	7.76	7.06
10	10.93	9.95
20	10.90	9.92

Note:
[a] Extrusion rate 5 cm (2 in.)/min
[b] At 225°C.

Table 4. Specific energy consumption data for different biomass materials.[10]

Materials	Densification unit type	Specific energy consumption (kWh/t)	Source
Sawdust	Pellet mill	36.8	Reed & Bryant[56]
Municipal Solid Waste	Pellet mill	16.4	Reed & Bryant[56]
Bark + wood	Pellet mill	30–45	Miles & Miles[57]
Straws + binders	Pellet mill	37–64	Miles & Miles[57]
Straws	Pellet mill	22–55	Neale[58]
Grass	Pellet mill	33–61	Shepperson & Marchant[59]
Switchgrass	Pellet mill	74.5	Jannasch et al.[60]
Alfalfa	Pellet mill	30	Tabil and Sokhansanj[12]
Straws + binders	Cubing machine	75	Miles and Miles[57]
Grass	Cubing machine	28–36	Balk[61]
Cotton trash	Cubing machine	60	Miles and Miles[57]
Hay	Cubing machine	37	Miles and Miles[57]
Sawdust	Piston press	37.4	Reed *et al.*[50]
Straws	Screw press	150–220	Carre *et al.*[62]
Grass	Piston press	77	Shepperson & Marchant[59]
Straws + binders	Ram extruder	60–95	Miles & Miles[57]

biomass material densified using different densification systems is shown in Table 4. Among these different systems, the screw press consumes the most energy because it involves not only compression but other forces like shearing and mixing. The pellet mill consumes the least energy. The chemical composition of biomass and methods of pretreatment before densification also significantly influence the specific energy consumption.

Densification system variables

Pellet and briquette presses are commonly used systems to create a uniform feedstock commodity with specific characteristics for bioenergy applications. Controlling the pelleting and briquetting system variables, including both process and feedstock variables, plays an important role in achieving the desired density, durability, and quality.[63] For example, Shaw[64] identified that process variables (die temperature, pressure, and geometry), feedstock variables (moisture content and particle size/shape), and feedstock composition (protein, fat, cellulose, hemicelluloses, and lignin) play an important role in the quality of the densified biomass.

Process variables

Temperature

Quality attributes like durability and bulk density of densified biomass are significantly influenced by temperature. Hall and Hall[65] found that for a given moisture content, the pressure required to obtain a certain wafer density of Bermuda grass and alfalfa was reduced by the addition of heat in the die. In addition, the upper limits of moisture content at which a certain pressure was able to produce a specific wafer density was increased by the addition of heat. Smith *et al.*,[66] in their study of briquetting wheatstraw, found that the degree of compaction and dimensional stability went up as the temperature was increased from 60 to 140°C. They also found that briquette expansion decreased when the die temperature was between 90 and 140°C. They further observed that briquettes were surface-charred and slightly discolored at temperatures above 110°C due to chemical degradation. Tabil[11] found that pelleting temperatures >90°C significantly improved durability values of alfalfa pellets. They concluded that it is necessary to precondition the grinds to above 90°C to promote better bonding of particles and to produce good durable pellets. Kaliyan and Morey[67] used the glass transition temperature of the lignin to understand the densification behavior. Their studies included three different temperatures: two within the glass transition temperature (75 and 100°C) and one outside (150°C). The durability values of the densified biomass outside the glass transition temperature were lower compared to ones within the range.

Pressure

Pressure plays an important role on the quality of pellets made from agricultural biomass. Yaman *et al.*[68] in their study of fuel briquettes from olive refuse and paper mill waste suggested that there is an optimum briquetting pressure above which may result in fractures due to dilation. High pressures and temperatures during densification may develop solid bridges by a diffusion of molecules from one particle to another at the points of contact, which increases density. Li and Liu[9] observed that compression of oak sawdust at pressure application rates of 0.24 to 5.0 MPa/s had a significant effect on the dry density of the product. For compaction of biomass waste materials like waste paper, Demirbas *et al.*[69] observed that increasing the pressure from 300 to 800 MPa on biomass with ~7% moisture (w.b.) initially increased the density sharply, from 0.182 to 0.325 g/ml, and then further increased it slightly to 0.405 g/ml. Butler and McColly[70] observed that the density of pellets is directly proportional to the natural logarithm of the applied pressure and increasing the pressure increased the unit density significantly.

Retention or hold time and relaxation time

The quality of briquettes is influenced by the retention or hold times of the materials in the die.[13] However, Al-Widyan *et al.*[71] found that the retention times between 5 and 20 s did not have a significant effect on olive cake briquette durability and stability. Li and Liu[9] found that the hold time for oak sawdust had more effect at lower pressures than at higher pressures. At the highest pressure (138 MPa), the effect of holding time was negligible. They also observed that the holding time had little effect on the expansion rate. A 10-s holding time could result in a 5% increase in log density, whereas at holding times longer than 20 s, the effect diminished significantly.

In general, relaxation time impacts the density of materials. Final relaxed density of briquetted fuel and the relaxation behavior following removal from the die depend on many factors related to die geometry, the magnitude and mode of compression, the type and properties of the biomass material, and storage conditions.[64] Many studies on high-pressure compaction of biomass materials indicate that upon removal of the material from the die, the density of the product decreases with time to a final relaxed density.[64] For most feed materials, the rate of expansion is highest just after the removal of pressure and decreases with time until the particle attains constant volume.[57,62] The relaxation characteristics, which are mainly measured by the percentage of elongation and increase in voidance, depend on many factors related to the feed material and storage conditions, such as relative humidity.[72] Shrivastava *et al.*[73] used statistical analysis of rice husks to establish a multiple correlation equation in the form of:

$$Y = \alpha_0 + \alpha_1 P + \alpha_2 T \qquad (5)$$

where Y is the percent volume expansion; T (°C) and P (kg/m^2) are the die temperature and pressure, respectively; and α_0, α_1 and α_2 are constants.

Die geometry and speed

Die geometry refers to the size and shape of the die. These dimensions affect the amount of material that can be pelleted and the energy required for compression. Die geometry also influences product properties like moisture content, bulk density, and durability. The L/D (length to diameter) ratio of the pellet die can be a good metric for the degree of compression during pelletization. An increase in the length of the pellet die increases the pelleting pressure, whereas an increase in the diameter of the pellet die decreases the pelleting pressure. Hence, the dimensions of the die and the press channels in the matrix have a strong influence on determining the pressure needed to press pellets through the matrix.[74]

Butler and McColly[70] found that for a constant mass of material, pellet density and length were greater for smaller diameter chambers at a given pressure. Tabil and Sokhansanj[13] studied the effect of process parameters like steam conditioning, die geometry, L/D ratio, die speed, and particle sizes of the biomass and found that at higher conditioning temperatures (>95°C) the durability of the pellets increased. They also concluded that the durability of the pellets improved when a smaller die with higher L/D ratios was used. Hill and Pulkinen[75] reported that the durability of alfalfa pellets increased by about 30–35% at an L/D ratio between 8 and 10. Heffiner and Pfost[76] evaluated the effect of three die sizes (4.8 × 44.5, 6.4 × 57.2, and 9.5 × 76.2 mm) on durability, finding that pellets produced on the smallest die had the best durability values. In their study of distillers' dried grains with solubles (DDGS), Tumuluru *et al.*[77] found that a larger die diameters of 7.2 mm produced less durable DDGS pellets compared to a smaller die diameter of 6.4 mm, both with and without the addition of steam.

Feedstock variables

Moisture content

Moisture content plays an important role on pellet formation.[78] Moisture in the biomass facilitates starch gelatinization, protein unfolding, and fiber solubilization processes during densification. Steam-treated biomass is superior to raw biomass because the additional heat modifies the physiochemical properties to the extent that binding between particles is enhanced, resulting in improved densification quality.[25] Mani *et al.*[10,79] observed that moisture in the biomass during densification increases the bonding via van der Waal's forces, thereby increasing the contact area of the particle. They also found that low moisture biomass (5–10%) resulted in denser, more stable, and more durable briquettes compared to higher moisture biomass (15%). Li and Liu[9] recommended an optimum moisture content of ~8% to produce high-density briquettes. They also recommended a moisture content of 5–12% to produce good quality logs in terms of density and long-term storage properties from hardwood, softwood, and bark.

Densification at optimum moisture content coupled with temperature may result in increased lignin melting and improve the binding characteristics. Kaliyan and Morey[78] suggest that moisture in biomass affects the glass transition temperatures during densification. They have found that at optimum moistures of 10–15% in corn stover, the glass transition temperature decreased and resulted in better binding at lower temperatures of 70–90°C. Chirife and Del Pilar[80] observed that increase in moisture content significantly decrease the glass transition temperatures of lignin, starch, and gluten. The effect of biomass moisture content on densification can be three-fold: (i) lowers the glass transition temperature; (ii) promotes solid bridge formation; and (iii) increases the contact area of particles by van der Waal's forces.

Particle size, shape, and distribution

In general, the density and durability of pellets is inversely proportional to the particle size because smaller particles have greater surface area during densification. MacBain[81] and Payne[82] concluded that medium or fine-ground materials are desirable in pelleting because they have greater surface area for moisture addition during steam conditioning, which increases starch gelatinization and promotes binding. They also reported that a certain percentage of fines to medium particle sizes improves pelleting efficiency and reduces pelleting cost. However, very small particles can lead to jamming of pellet mills and affect production capacity. Table 5 indicates the particle size distribution for producing good quality pellets.[83]

Table 5. Optimum particle size distribution for producing quality pellets from agricultural biomass.[83]

Sieve size (mm)	Material retained on sieve
3.0	≤1%
2.0	≤5%
1.0	≈20%
0.5	≈30%
0.25	≈24%
<0.25	≥20%

In the case of briquette presses, bigger particles sizes (>6 mm) are desirable, leading to better interlocking of the particles and increasing the durability. Using wheat, oats, barley, and canola, Song *et al.*[35] indicated that particle sizes between 19.05–31.15 mm resulted in good quality briquettes using a hydraulic piston press. They also concluded that larger particle sizes during briquetting help in interlocking particles and produce a more durable briquette.

Biomass composition

Feedstock composition contributes significantly to the quality of densified materials. Raw biomass has both low molecular weight and macromolecular compositions. Low molecular weight substances include organic and inorganic matter, while macromolecular substances include cellulose, hemi-cellulose, and lignin.[84] Understanding the major compositional changes that take place during biomass processing can be useful in understanding their compaction behavior. Thomas *et al.*[85] identified some of the important ingredients that influence pellet quality, including starch, protein, non-starch polysaccharides (NSP), sugar, fat, fiber, inorganic matter, and water. Tables 6 and 7 show the composition of some agricultural and woody biomass. Wood is shown to have higher lignin content than other biomass materials, and straws are shown to have a certain percentage of protein content, both of which can promote binding.

Starch

Starch is a D-glucose polymer with branched (amylopectin) or un-branched (amylose) chains.[86] Its behavior is mainly controlled by the gelatinization it undergoes at high processing temperatures. Starch granules at high temperatures and moistures influence the binding properties

Table 6. Chemical composition of selected agricultural straws.[27]

Composition (% DM[a])	Barley straw	Canola straw	Oat straw	Wheat straw
Protein	3.62	6.53	5.34	2.33
Fat	1.91	0.69	1.65	1.59
Starch	0.11	0.34	0.12	2.58
Lignin	17.13	14.15	12.85	13.88
Cellulose[b]	33.25	42.39	37.60	34.20
Hemicellulose[c]	20.36	16.41	23.34	23.68
Ash content	2.18	2.10	2.19	2.39

[a] DM – dry matter.

[b] Cellulose percentage is calculated indirectly from percentage ADF and lignin (%ADF-%lignin).[10]

[c] Hemicellulose percentage is calculated indirectly from percentage Neutral detergent fiber (NDF) and acid detergent fiber (ADF): (%NDF -%ADF).[10]

Table 7. Biochemical composition of herbaceous and woody biomass.[84,147]

Plant material	Lignocellulosic content (%)		
	Hemicelluloses	Cellulose	Lignin
Orchard grass (medium maturity)	40.0	32.0	4.7
Rice straw	27.2	34.0	14.2
Birch wood	25.7	40.0	15.7
Scots pine	28.5	40	27.7
Spruce	30.6	39.5	27.5
Eucalyptus	19.2	45	31.3
Silver birch	32.4	41	22

of many foods and feeds. Gelatinization of starch is an irreversible process and influenced by densification process variables like heat, water, shear, and residence time.[87] During pelletization, starch not only acts as a binder but also as a lubricating agent, helping to ease the flow of materials through the die. In the pharmaceutical industry, starch is widely used as a binder or filler in tablet formulations.[88]

Protein

Protein that is heated during the densification process undergoes denaturization, leading to the formation of new bonds and structures with other available proteins, lipids, and starches, helping to improve the binding capacity.[85,89] According to Briggs *et al.*[23] and Wood,[24] increasing the protein content increases the pellet durability. Raw protein improves the physical quality of the pellets compared to denatured proteins. Tabil[11] reported an improvement in the binding properties of the material if sufficient natural proteins are present during pelletization. Sokhansanj *et al.*[90] identified that feed material, which contain higher proportions of starch and protein, will produce more durable and higher quality pellets than biomass containing only cellulosic material. They also concluded that the optimum moisture content for pelleting cellulosic materials is 8–12%, whereas for starch and protein materials (mostly animal feeds), the optimum moisture can range up to 20%.

Lipid/Fat

Fat content in biomass acts as a lubricant during pelletization, increasing throughput, and reducing pelleting pressure.[11] However, higher fat content can hinder binding. Briggs *et al.*[23] found that increased oil content produced lower quality pellets since fat is hydrophobic and tends to interfere with particle binding during pelletization.

Cellulose

Cellulose is an organic, polysaccharide compound ($C_6H_{10}O_5$) consisting of a linear chain of several hundred to over ten thousand $\beta(1\rightarrow4)$ linked D-glucose units.[91,92] Cellulose forms crystalline microfibrils that are surrounded by amorphous cellulose inside plant cells.[93] The structural integrity of cellulose is produced by hydrogen bonding that occurs between the glucose monomers.[94] According to Nelson and Cox[95] cellulose is considered to be an abundant source of carbon in biomass. Semi-crystalline structure and highly hydrogen bonded cellulose itself is not a suitable adhesive, but this limitation can be overcome by heat treatment in the drying range, making the cellulose molecule more flexible.[96]

Hemicellulose

Hemicellulose is any of several heteropolymers (matrix polysaccharides), such as arabinoxylans, present along with cellulose in almost all plant cell walls. While cellulose is crystalline, strong, and resistant to hydrolysis, hemicellulose has a random, amorphous structure with little strength. It is easily hydrolyzed using a dilute acid or base as well as many hemicellulase enzymes. The amorphous structure of hemicelluloses – which is easily hydrolyzed or dissolved in alkali solution – results from branching. Some researchers believe that natural bonding may occur due to the adhesive products produced by degradation of hemicellulose.[33]

Lignin

Lignin is a complex chemical compound most commonly derived from wood and an integral part of the secondary cell walls of plants and some algae.[97,98] Lignin is a random network polymer with a variety of linkages based on phenyl propane units.[99] The lignin molecule provides many structural purposes, such as, acting like glue, to the cellulose fibers. Lignin plays a crucial part in conducting water in plant stems. The polysaccharide components of plant cell walls are highly hydrophilic and thus permeable to water, whereas lignin is more hydrophobic, which helps improve storage behavior.

Lignin helps in building solid bridges at elevated temperatures and plays a significant role in biomass densification. Lignin is the component that permits adhesion in the wood structure and acts as a rigidifying and bulking agent. It is, in general, believed that highly lignified wood is more durable and therefore a good raw material for many applications. It is also an excellent fuel, because lignin yields more energy when burned than cellulose. The presence of lignin in plant materials allows pelletization without adding binders (Table 7). Van Dam *et al.*[26] reported that lignin exhibits thermosetting properties at working temperatures of >140°C and acts as an intrinsic resin, producing more durable pellets.

It is believed that higher lignin levels lead to more durable pellets because lignin acts as the 'glue' that binds particles together. However, Lehtikangas[100,101] reported a loose correlation between lignin content and pellet durability. Similarly, Wilson[102] concluded that there is no consistent relationship between lignin content and pellet durability for hard and softwoods, but that a mixture of woody biomass with higher lignin content gave less durable pellets compared to pure samples. Figures 9 and 10 show the effect of different lignin and moisture contents on pellet durability in pure and mixed species.[102] Bradfield and Levi[103] reported that when lignin plus extractives content increased above a threshold level of 34% in wood samples, the pellet durability decreased.

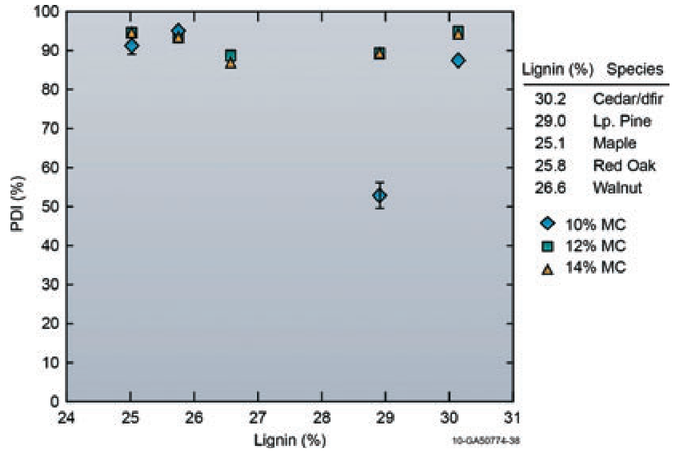

Figure 9. Pellet durability versus lignin in pure species.

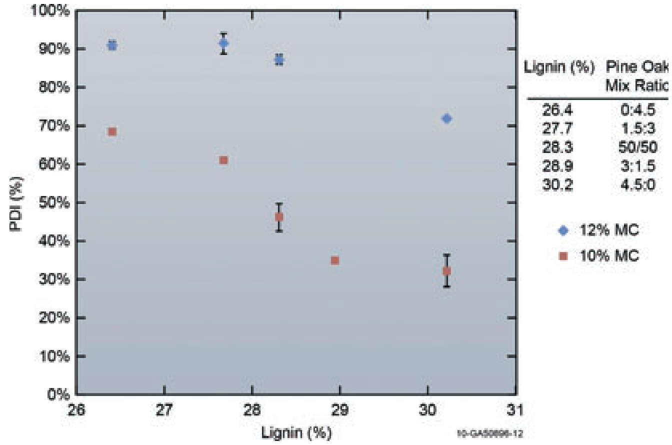

Figure 10. Pellet durability versus lignin in mixed species.

Binders used in biomass densification

Binders improve the cohesive characteristic of biomass by forming a gel with water, helping produce a more durable product. Binders also help reduce the wear on production equipment and increase the abrasion resistance of the fuel. In general, binders are allowed in a fuel feedstock but need to be specified as part of the final product. The most commonly used binders in pellet making are lignosulphonates (Wafolin), or sulfonate salts made from the lignin in pulp mill liquors.[104,105] Lignosulfonates, considered the most effective binders, are used in animal feeds.[63,106] The general quantity to include for effective binding ranges from 1–3%. Bentonite, or colloidal clay, is commonly used as a binder in feed pelleting and is made up of aluminum silicate composed of montmorillonite. As mentioned previously, proteins are natural binders that are activated through interactions with other biomass compositions, such as lipids and starches, and the heat produced in the dies. Some agricultural biomass, like alfalfa, has a high protein content and can be used as a binder to improve the durability of pellets made from lower lignin content biomass materials.

Pre-treatment of biomass

Pre-treatment plays an important role in densification because it prepares lignocellulosic biomass for different densification systems. Pre-treatment helps reduce the specific energy consumption and produce different high-quality densified products for different end-use applications. In general pre-treatment improves the quality attributes (higher durability and bulk and energy densities), storage and handling characteristics, and transportation logistics. Some promising pre-treatment methods for bioenergy applications include (i) grinding, (ii) pre-heating/steam conditioning, (iii) steam explosion, (iv) torrefaction, and (v) AFEX. Integrating pre-treatment with a densification process can help address many storage, handling, and transportation logistics challenges.[107]

Grinding

Prior to densification, biomass is ground to a certain particle size. This grinding partially breaks down the lignin, increases the specific area of the materials, and contributes to better binding. Peleg,[108] Peleg and Mannheim,[109] and Mani *et al.*[10] concluded that particle size has a significant effect on the binding characteristics and the mechanical properties of pellets. Fine powders have advantages because they have a higher number of contact points, more exposed surface area, and greater surface energy per unit of weight regardless of their physical and chemical characteristics.

Pre-heating/steam conditioning

Pre-heating biomass before densification is widely used as it results in a higher quality product. Most commercial pellet or briquette producers use pre-heating to form more stable and dense product.[110,111] Aqa and Bhattacharya[55] indicate that pre-heating could increase the throughput of densification and reduce the energy required per kilogram of product formed. Steam conditioning is a process where steam is added to the biomass to make the natural binder, lignin, more available during densification.[112] It is postulated that by disrupting lignocellulosic biomass materials via steam conditioning will improve the compression characteristics of the biomass.

Steam explosion

Steam explosion is a technique where high pressure steam is introduced into a reactor for a short period of time and then released, causing the material to expand rapidly.[113] This process produces significant physical, chemical, and structural changes in the biomass and makes lignin more available for binding during pelletization.[112] In addition, steam explosion breaks the lignin down into low-molecular weight products that retain their basic structure and are moderately reactive. Mosier *et al.*[114] postulated that the compression and compaction characteristics of biomass can be improved through steam explosion pre-treatment. According to Zandersons *et al.*,[99] the activation of lignin and changes in cellulose structure during steam explosion help form new bonds, which in turn create more durable pellets.

Steam explosion also has benefits in terms of enzymatic hydrolysis. Lignin is extensively depolymerized by cleavage of the β-aryl-ether bonds, making it soluble in alkaline solutions or certain organic solvents. In addition, hemicellulose is partially broken down, making it soluble in water and allowing it to condense with lignin, thereby increasing the lignin content. The major effect of steam explosion is the large increase in the accessibility of cellulose to enzymatic hydrolysis.[115–118] Kaar *et al.*[119] noted that steam explosion requires little or no chemical input, making it more environmentally friendly than chemical treatment methods. Thus, steam explosion is a beneficial pre-treatment option because it causes hemicelluloses to become more water soluble and makes cellulose and lignin more accessible through depolymerization.[120]

Torrefaction

Torrefaction is the slow heating of biomass in an inert environment to a maximum temperature of 300°C.[121–123] Torrefaction removes most of the smoke-producing compounds and other volatiles, resulting in a final product that has approximately 70% of the initial weight and 80–90% of the original energy content.[124,125] The major decomposition reactions affect the hemicelluloses, and, to a lesser degree, the lignin and cellulose.[126,127]

Torrefaction helps to develop a uniform feedstock and improves binding during pelletization by increasing the number of available lignin sites, breaking down the hemicellulose matrix, and forming fatty unsaturated structures, resulting in bulk densities of 750–850 kg/m^3 and energy densities exceeding 20GJ/m^3.[128,129] Bergman[130] indicated that torrefaction results in weakened biomass polymers (i.e., less fibrous and more plastic) and catalyzes chemical modifications that lead to more fatty structures, which act as binding agents during densification. In addition, the lignin content increases typically 10–15% as the devolatilization process during torrefaction leads to degradation of hemicellulose. Studies of densification of torrefied biomass at 250°C indicated that the pressure and energy required for densification can be reduced by a factor of two and the throughput increases by two times compared to raw biomass densification using a pellet mill.[56,128,130] These researchers also indicated that heating the material to temperatures >250°C during densification is not recommended as it leads to heavy devolatilization.

Ammonia fiber explosion (AFEX)

AFEX pre-treatment of the biomass (ammonia fiber explosion) uses aqueous ammonia at elevated temperatures and pressures[131] to produce higher hydrolysis yields for many herbaceous feedstocks. This process reduces lignin and removes some hemicellulose while decrystallizing cellulose in the biomass. The major advantage of this process is little biomass degradation.[132] The process offers other advantages like elimination of a separate liquid phase and the possibility of very high solids loading. The resulting dark black product may offer improved densification characteristics because it opens the cellulosic structure and makes more lignin sites available for binding. Eranki *et al.*[107] in their study on advanced biomass processing depots evaluated densifying AFEX products to solve storage and transportation logistics.

Physical attributes of densified biomass

Moisture content (%)

The optimum final moisture content of densified biomass is very important and greatly depend on process conditions like initial moisture content, temperature, and pressure. Higher moisture in the final product results when the initial moisture is greater than 15%. Mani *et al.*[10] observe that initial moisture >15% and pressure >15 MPa has a negative effect on the final briquette quality where cracks occur. Lower moisture in the pellets (<5%) can result in revenue loss as pellets tend to break up, creating more fines during storage and transportation. Pellets with high moisture content can be subject to spoilage due to microbial decomposition, resulting in significant dry matter loss during storage and transportation.[133]

Unit and bulk density (kg/m^3)

Unit density and bulk density are important parameters for storage and transportation. Several researchers have found that these parameters are greatly influenced by the material's moisture content and particle size, and the process pressure and temperature.[10,134] Generally they found that materials with higher moisture and larger particle sizes reduce the unit and bulk density of the product, while higher process temperatures and pressures increase the unit and bulk density. Rhen *et al.*[134] also found that high dry unit density corresponds to high compression strength. Tumuluru *et al.*[135] in their article on pelleting DDGS, supported the conclusions that both unit and bulk density is dependent on feed moisture and die temperature, where a maximum unit density of 1200 kg/m^3 and bulk density of 700 kg/m^3 is achievable at temperatures of about 100°C and feed moistures of about 5–7%.

Durability index (%)

The durability index is a quality parameter defined as the ability of densified materials to remain intact when handled during storage and transportation. Thus, pellet durability is its physical strength and resistance to being broken up. Durability or abrasive-resistance measurements help simulate either mechanical or pneumatic handling forces to help or control feed quality. Different types of equipment (Holmen tester, tumbling can, Ligno tester and Dural tester) are used to test durability.[78]

Moisture increase durability when water soluble compounds, such as sugar, starch, soda ash, sodium phosphate, potassium salt, and calcium chloride, are present in the feed.[78] High starch content acts as a binder and increases durability. However, native starch has less binding capacity than gelatinized starch, where moisture and heat accelerate the process.[26,85,136,137] Protein will plasticize with heat and moisture and act as a binder, increasing the durability of the products.[23,138] Furthermore, high fat content will result in low durability, as fat acts as a lubricant between the feed particles and die wall.[23,139–142]

Lignin, at elevated temperatures (140°C), acts as a binder and increases durability. However, Bradfield and Levi[103] observe that when the lignin content and other extractives increase to more than 35%, the durability values decrease. They postulate that the auto-adhesive nature of lignin and other extractives decreases at higher concentrations due to their excessive mastic nature. Pre-heating or steam conditioning increases the activity of inherent binders like lignin and starch, thus producing more durable pellets. Pre-heating temperatures are usually restricted to 300°C to limit the decomposition of the biomass.[78] Steam conditioning also helps to release and activate natural binders and lubricants in the feed, thus increasing starch gelatinization, protein denaturation and pellet durability.[78] Finally, particle size and process variables, such as die dimensions, L/D ratios, and rotational speeds, also influence durability values.[19,78,79]

Percent fines (%)

The presence of fines in the densified product is not desirable, especially when co-firing with other fossils fuels. Fines are generated during transportation and storage by the breakdown of the densified product. Pellets processed under suboptimal conditions, such as lower moisture lower temperatures, and with less desirable chemical compositions or with insufficient die size and roller speeds, are less durable and can result in more fines in the final product. Once the percent fines cross the storage threshold value in silos, spontaneous combustion and dust explosion problems can occur. Tumuluru *et al.*[77] in their studies on the effect of storage temperature on the quality of wood pellets found that higher storage temperatures (30–50°C) increase the percent fines by more than 1%.

Calorific value (MJ/kg)

In general, the caloric value of pellets and briquettes depends on process conditions like temperature, particle size, and feed pre-treatment. Generally, pellets with higher density have higher caloric value. The typical calorific values of wood- and straw-based pellets range from 17–18 MJ/kg.[77,143] Many researchers have observed that pre-treatment processes like steam explosion or torrefaction prior to densification increases the calorific value to 20–22 MJ/kg.[113,144,145]

Table 8 indicates the methods recommended by European Common Standard for Solid Fuel (CEN) and Pellet Fuel Institute (PFI in North America) for measurement of the physical properties discussed.

Table 8. Standards recommended for measuring densified biomass quality.

S. No	Pellet Quality	Common European Standard (CEN)[a]	Pellet Fuel Institute (PFI)[b]
1	Moisture content	CEN/TS 15414-1:2010	ASTM E 871 Standard Test Method for Moisture Analysis of Particulate Wood Fuels
2	Bulk density	CEN/TS 15401:2010	ASTM E 873 Standard Test Method for Bulk Density of Densified Particulate Biomass Fuels.
3	Durability	CEN/TS 15639:2010	Kansas State University - Mechanical Durability of Feed Pellets, Call Number: LD2668.T4 1962 Y68) for assessing the durability of residential/commercial densified fuel products, with the exception that the screen size used in determining durability has been modified to be a 1/8-inch (3.17 mm) wire screen sieve.
4	Percent fines	3.15 mm screen	1/8-inch (3.17 mm) wire screen sieve
5	Calorific value	EN 15400:2011	ASTM E 711 Standard Test Method for Gross Calorific Value of Refuse-Derived Fuel by the Bomb Calorimeter

Note: Unit density is not a standard followed by PFI and CEN, but the American Society of Agricultural and Biological Engineers (ASABE) has a standard procedure (ASAE S269.4) for measuring unit density of pellets and briquettes.

Source:
[a] CEN/TC 343 - Published standards;
[b] PFI Standard Specification for Residential/Commercial Densified Fuel, October 25, 2010.

International standards for densified solid fuels

The standards for densified biomass application as a solid fuel in USA are given by the PFI and in Europe by CEN. PFI standards discuss specifications for densified fuel for residential and commercial applications, but do not specify whether it is in a pellet, briquettes, or densified log form. On the other hand, the European Committee for Standardization[146] prepared testing methods and technical specifications for solid biofuels specifically for pellets and briquettes. Tumuluru *et al.*[133] have reviewed the existing PFI and CEN standards for pellets and briquettes in their article on biomass densification technologies for bioenergy applications. Further standards need to be developed for densified biomass produced using other densification systems, which can include (i) a cuber,

(ii) an agglomerator, (iii) a tablet press, and (iv) a screw press, which can help develop a consistent uniform feedstock commodity product for energy applications.

Discussion

A comparison of various densification systems in terms of feedstock properties, specific energy consumption, processing additives, and suitability of the densified material for different end-use applications is shown in Table 9. All densification systems reviewed in this study help in developing an advanced uniform feedstock with bulk flow characteristics for bioenergy applications. Even though the unit densities of pellets, briquettes, and cubes are similar (1.0–1.2 kg/m^3), pellets have higher bulk densities and offer advantages in terms of storage, handling, and transportation logistics. On the other hand, briquette presses can handle bigger particle size and higher moisture contents, giving them an advantage over other densification systems like pellet mills, screw presses, and agglomerators. Table 9 shows that screw-pressed material is more suitable for co-firing and combustion because the biomass is carbonized during densification, whereas the pellet, roller, and piston-pressed materials are more suitable for biochemical and thermochemical conversion processes.

The use of roller presses, tabletizers, and agglomerators for energy applications is still in the early stages of research, and more detailed studies in terms of process and feedstock variables are needed to understand the suitability of these systems. Data on energy consumption is also not readily available. Literature from other industries provides some indication of the promise of these systems. For example, though there is no specific information on the properties of agglomerates made from biomass, their suitability mentioned in Table 9 takes into account physical properties like size, shape, and bulk density determined for the pharmaceutical industry. Finally, binders will play an important role in some, if not all, of the densification systems, particularly agglomerators and roller presses, which some studies indicate will require the addition of a binder to improve the durability and bulk density. The extent of the role of binders, however, needs further evaluation. Thus, thorough research on the densified material properties and the effect of process variables on these densification systems is needed.

The specific energy consumption of different densification systems varies depending on the different unit operations involved, like compression, pushing, shearing, and mixing. The systems that involve more compression and pushing consume more energy because they depend on the dimensions of the pressing channel. About 40% of the energy is required for compressing the material and the remaining energy is required for overcoming friction during compression. Among the different densification systems, a screw press consumes the most energy because it not only compresses but also shears and mixes the material, whereas a pellet mill or cuber consume the least, depending on the material processed.

Densification process variables like temperature, residence time and application pressure play a vital role on the binding behavior. Higher temperatures of >200°C during densification can lead to charring of the densified biomass, rendering it unsuitable for some conversion processes. Knowing the end use of the material will help determine the appropriate temperature the biomass is exposed to. Another important variable that influences the quality of the densified biomass is retention time, where higher holding times of 5–20 s improve the density of the pellet or briquettes. Of course, a balance between holding times and machine capacity will have to be determined. Finally, higher pressures lead to higher product densities and are proportional to the natural logarithm of the applied pressure. However, higher pressures often require higher operating costs and higher machine wear requiring a trade-off in cost and product density.

Among the feedstock variables, moisture content and particle size have the greatest influence on the densification process. Moisture can lower the glass transition temperature, promote solid bridge formation, and increase the contact area of particles. Lowering the glass transition temperature of the biomass by managing the moisture content is a good way to densify biomass with less recalcitrance for the conversion process. In the case of particle size, different systems support different particle sizes. A pellet mill requires smaller particles because binding depends on the contact area between the particles, and briquette presses require larger particle sizes because the material bonds by interlocking. Thus, managing the material properties to suit the densification equipment will be crucial for getting the right quality of feedstock product and managing the cost of the system.

Table 9. Comparison of different densification equipments.[2,5,19,33,38,40,42,44,78,148]

	Pellet mill	Piston press	Roller press	Cuber	Tabletizer	Screw press	Agglomorator
Optimum moisture content of the raw material (%)	10–15	10–15	10–15	15–25	10–15	4–8	No information
Particle size requirements (mm)	<3	6–12	<4	12–16	<20	2–6	0.05–0.25
Addition of binder	Not required	Not required	Required	Required	Not required	Not required	Required
Shape	Cylindrical	Cylindrical	Generally Elliptical (depends upon the shape of the die)	Cylindrical	Cylindrical	Cylindrical	Spherical
Dimensions (mm)	4.8–19.1 (dia); 11–19 (length) 12.7 to 25.4 (length)	32 (dia) x 25 (thick)	Almond shaped briquettes dimensions: 31.75 (length) × 20.32 (width) × 11.16 (depth) (depends upon the shape of the die)	33 x 33 cross section and 25.4 to 101 (length)	100–150 (dia) 50 (length)	Length: 1940 Width: 750 Height: 1310 (Smaller dies produces smaller extruded logs)	2–6 (dia)
Wear of contact parts	High	Low	High	Low	Low	High	Low
Output from machine	Continuous	In strokes	Continuous	Continuous	In strokes	Continuous	Continuous
Specific energy consumption (kWh/ton)	16.4–74.5	37.4–77	29.91–83.1	28–75	High energy requirements (Still under research)	36.8–150	No information
Through puts (ton/hr)	5	2.5	5–10	5	0.5–1	0.5–1	No information
Unit density (g/cm^3)	1.1–1.2	<0.1	No information	0.8	1.2	1–1.4	No information
Bulk density (g/cm^3)	0.65–0.75	0.4–0.5	0.48–0.53	0.45–0.55	0.6–0.7	0.5–0.6	0.4–0.5
Maintenance	Low	High	Low	Low	Low	Low	Low
Combustion performance of briquettes	Very good	Moderate	Moderate	No information	No information	Very good	No information
Carbonization of charcoal	Not possible	Not possible	Not possible	Not possible	Not possible	Makes good charcoal	Not possible
Suitability in gasifiers	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable
Suitability for cofiring	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable
Suitability for biochemical conversion	Suitable	Suitable	Suitable	Suitable	Suitable	Not suitable	No information
Homogeneity of densified biomass	Homogeneous	Not homogenous	Not homogeneous	Not homogeneous	Not homogeneous	Homogenous	Homogenous

Pre-treatment of biomass before densification can play an important role in densification as well and can improve the binding characteristics of biomass that is low in lignin content. Some of the commonly used pre-treatment processes are grinding, pre-heating, steam explosion, steam conditioning, torrefaction and AFEX. Pre-treating biomass prior to densification improves properties like durability, bulk and energy density, and calorific value and reduces the specific energy consumption. Other promising methods of improving the binding characteristics include addition of natural or synthetic binders. Lignocellulosic biomass, which does not bind easily, can be improved by adding either natural or commercial binders like protein or lignosulfonates. Note that pre-treatment methods are generally required to produce a quality product.

International organizations like CEN and PFI have established standards to evaluate the quality of densified products like pellet and briquettes for solid fuel applications, but standards still need to be developed for the other systems, such as the cuber, screw press, table press, and roller press in relation to energy applications.

Conclusion

Among the technologies discussed in this review, the pellet mill and briquette press are most commonly used for biomass densification and make the product suitable for biochemical, thermochemical, and co-firing applications. In terms of energy consumption, a screw press consumes the most and pellet mill the least. Densification system variables, which include process variables (temperature, residence time and application pressure), feedstock variables (moisture content and particle size), and biomass composition (protein and lignin), have the greatest influence on binding characteristics. The densification behavior of low-lignin-content biomass material can be improved by pre-treating using steam conditioning, steam explosion, torrefaction, or AFEX. Addition of either natural or commercial binders is also a good alternative to improve the binding characteristics of low-lignin-content biomass while reducing the specific energy during densification. The important quality attributes of the densified biomass includes durability index, bulk density, moisture content, percent fine, and calorific value, which are evaluated using the existing international standards developed by PFI in the USA and CEN in Europe.

Even though densification of biomass has been in practice for a long time, there are still research gaps that need to be addressed in order to understand the interaction of feedstock, process variables, and pre-treatment methods on the quality of the densified biomass. The following research areas can help to advance the science of densification:

1. Explore the mechanisms of densification using SEM and TEM techniques.
2. Study the agglomeration technique by modifying material properties.
3. Evaluate the effect of torrefaction, steam explosion, and AFEX pre-treatment methods on material properties, densification behavior, and specific energy consumption.
4. Study glass transition temperatures of both raw and pre-treated biomass in relation to densification processes.
5. Examine process variable effects on quality attributes and specific energy consumption from tablet press, roller press, and agglomerator systems.
6. Develop new standards for densified biomass produced using cuber, tabletizer, roller press, and agglomerator systems.

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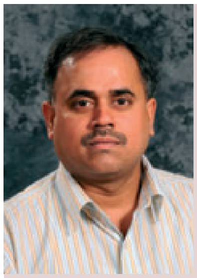

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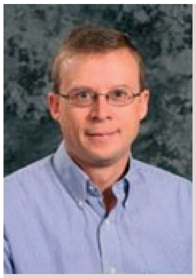

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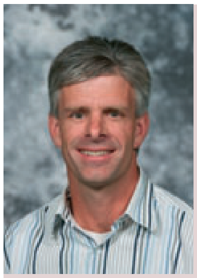

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